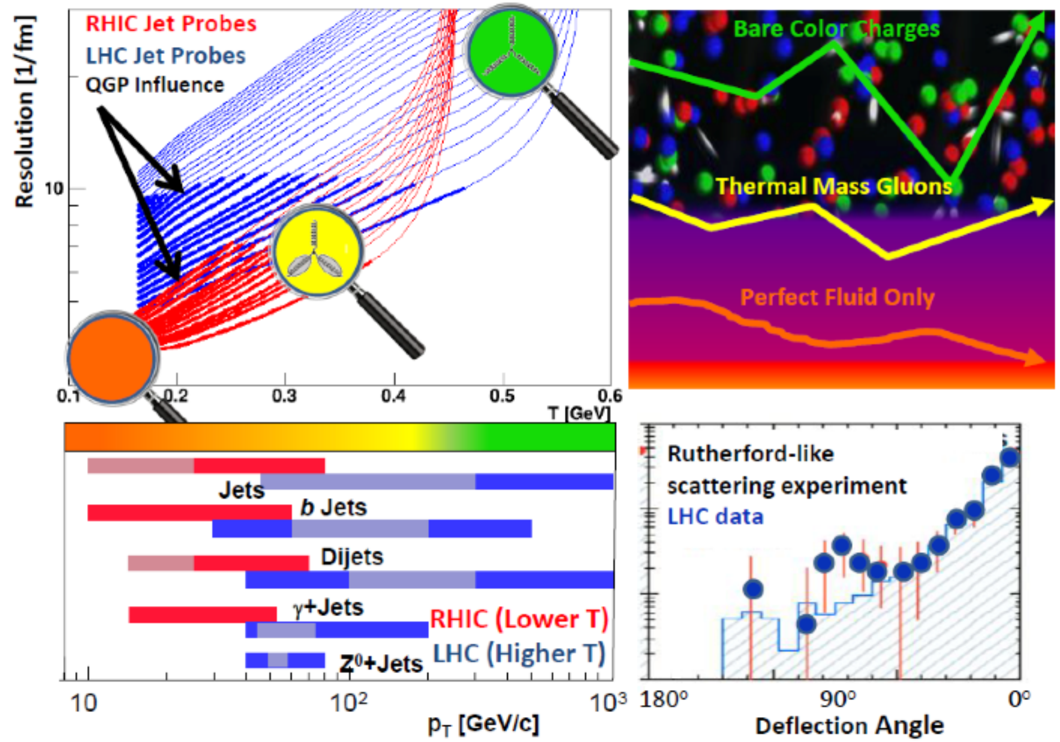
What can you do while things get started - Jets

Jörn Putschke

(Wayne State University)

The Science of sPhenix: In this talk focus on light flavor Jets



What did we learned from RHIC and LHC?

Do we have a (qualitative) consistent picture?

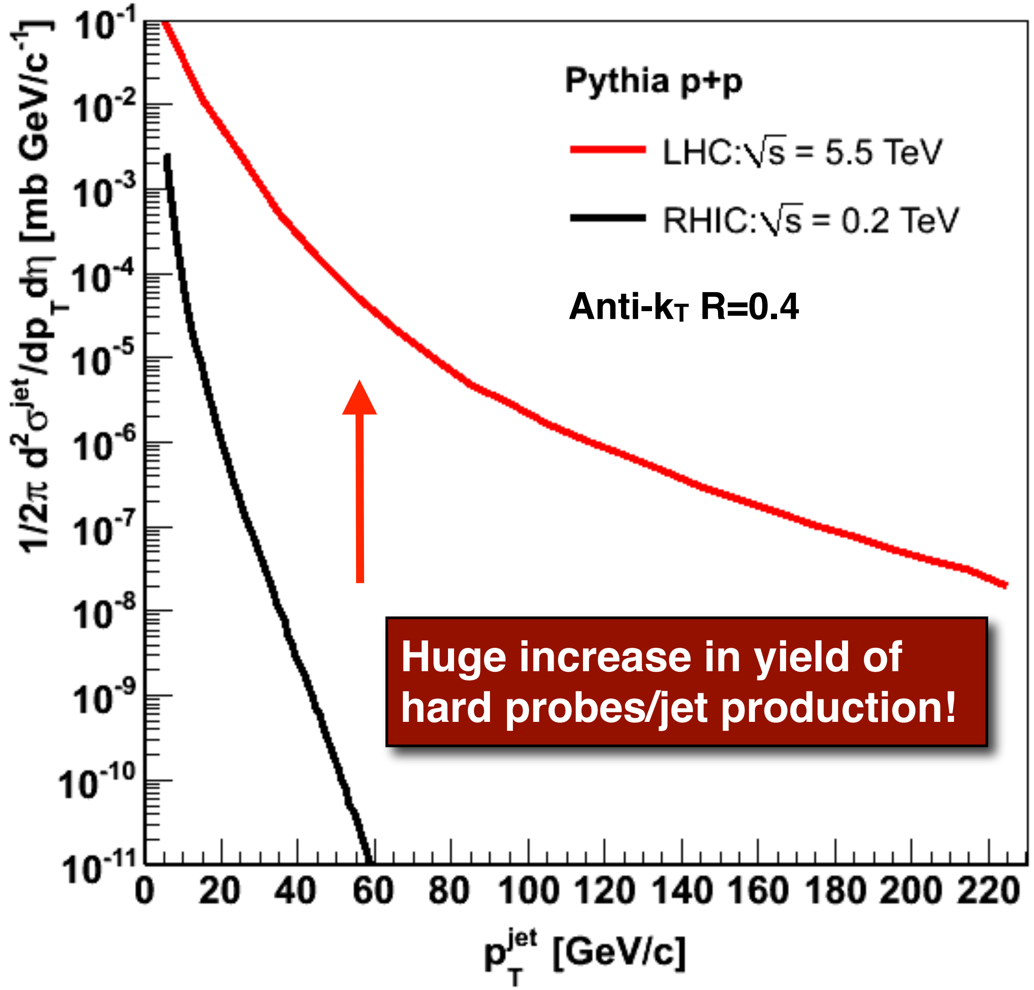
What (new) measurements can we perform utilizing the “strength” of RHIC/sPhenix?

RHIC and LHC "Jet Landscape"

The QGP at the LHC

• fireball hotter (~20%) and denser (~x2) and longer lifetime wrt RHIC

• bulk dynamics, $v_n(p_T)$, similar at RHIC and LHC, mainly driven by initial state "geometry"



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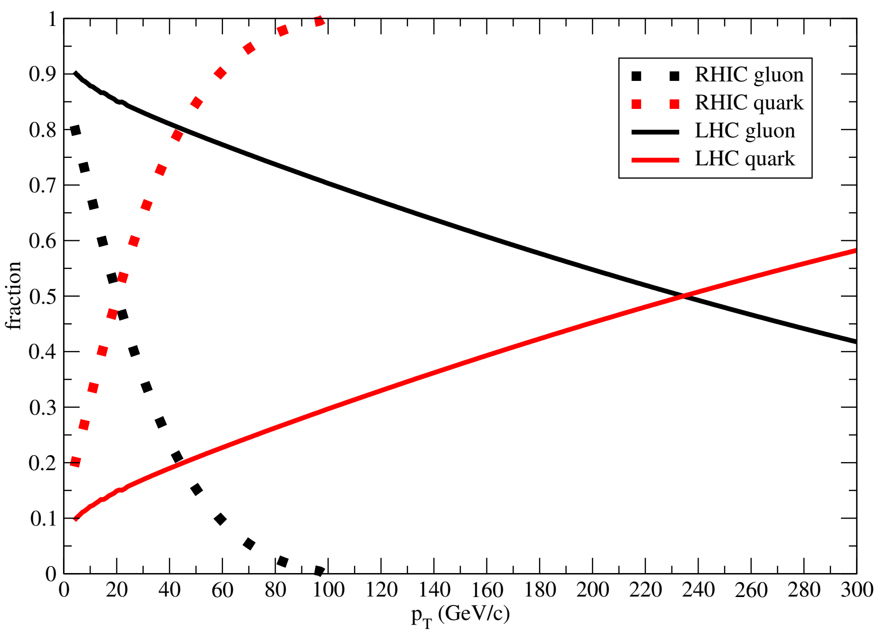
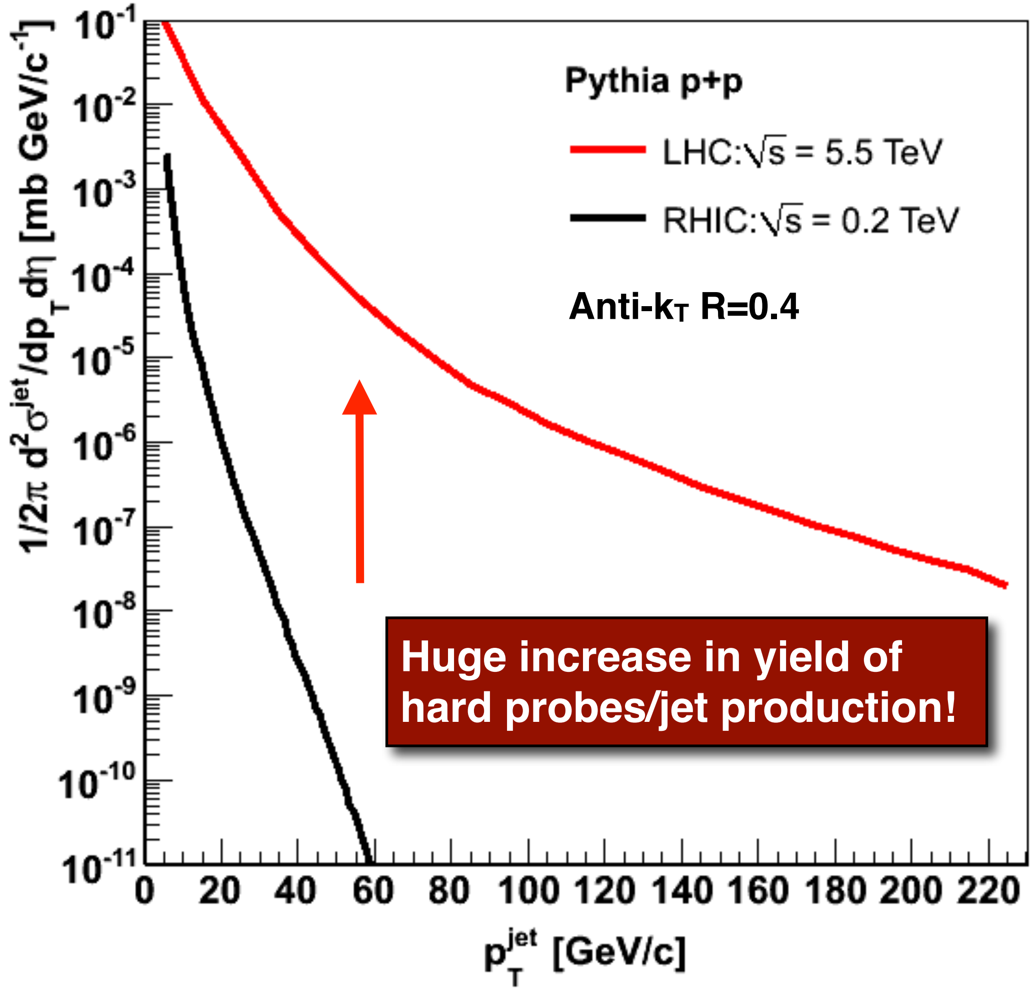


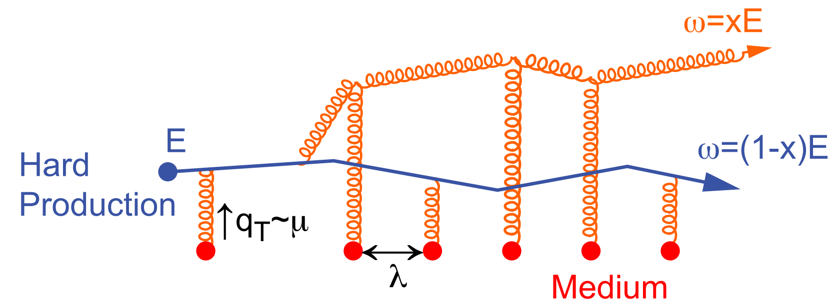


Mainly gluon jets (p_T<200 GeV) at the LHC.
Quark jets at RHIC p_T>40 GeV.

Naive: What is jet quenching?

Jet quenching = Gluon radiation:

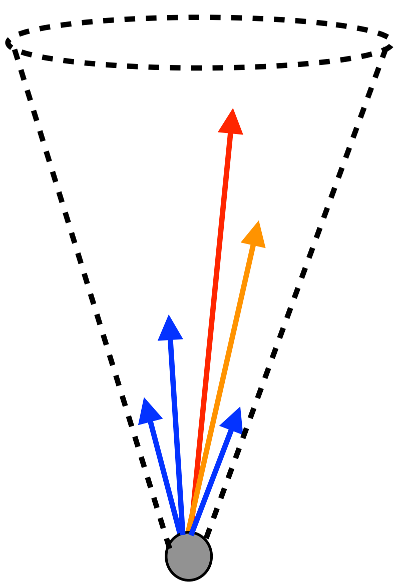
Multiple final-state gluon radiation off the produced hard parton induced by the traversed dense colored medium ~ “Gluon Bremsstrahlung”



→ Modification of the Jet Structure/Fragmentation Function
= fractional jet momentum carried by the individual jet particles/constituents

Jet in vacuum

E^{Jet}_{Vacuum}

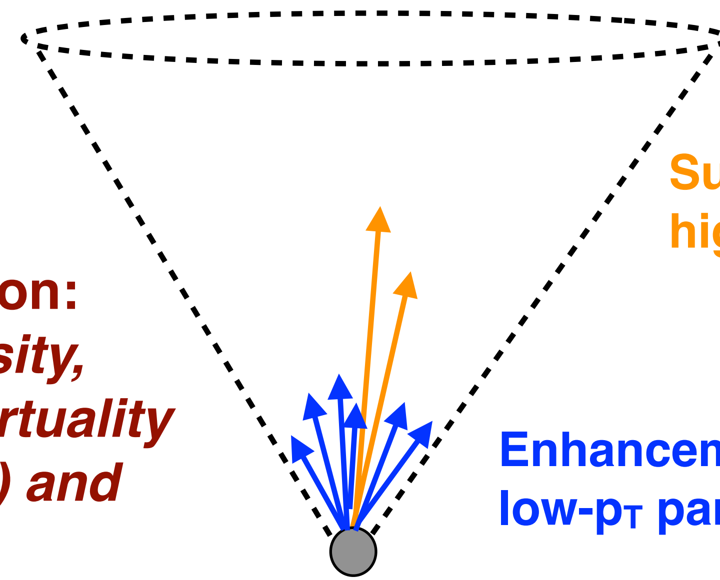


Jet quenching/ gluon radiation in QGP depends on:
path-length, density, parton energy, virtuality (resolution scale) and quark vs gluon
(gluons loose 9/4 times more energy)

Jet in medium

$E^{Jet}_{Medium} = E^{Jet}_{Vacuum}$

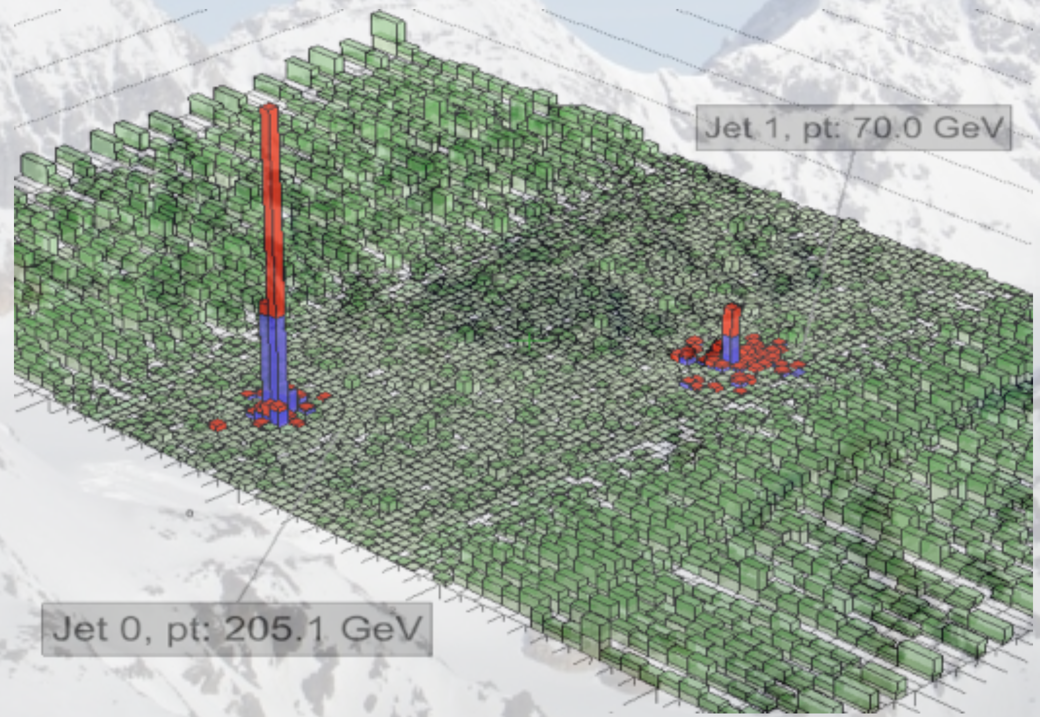
Jet broadening



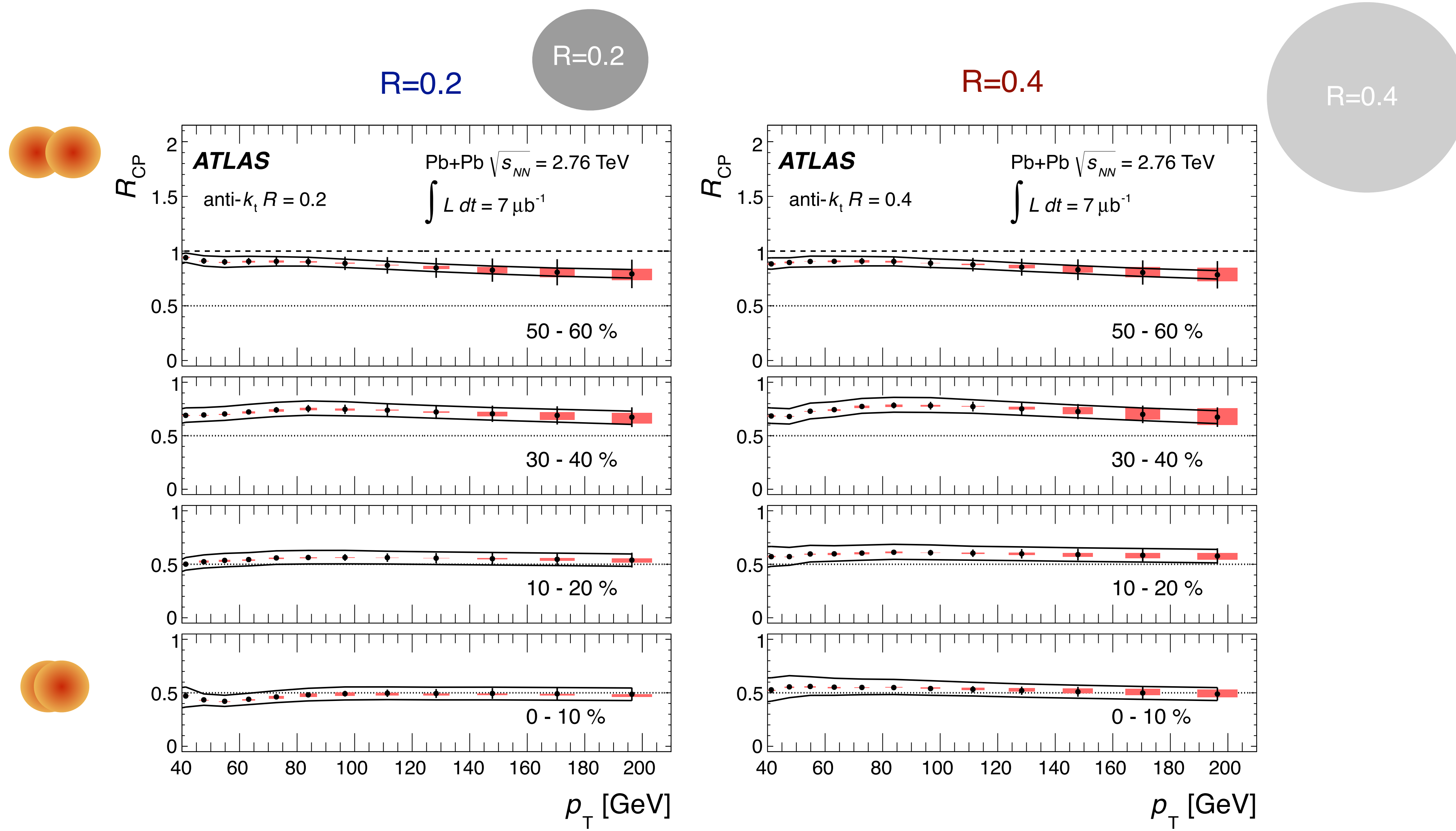
Suppression of high-p_T particles

Enhancement of low-p_T particles

Jet Measurements at the LHC



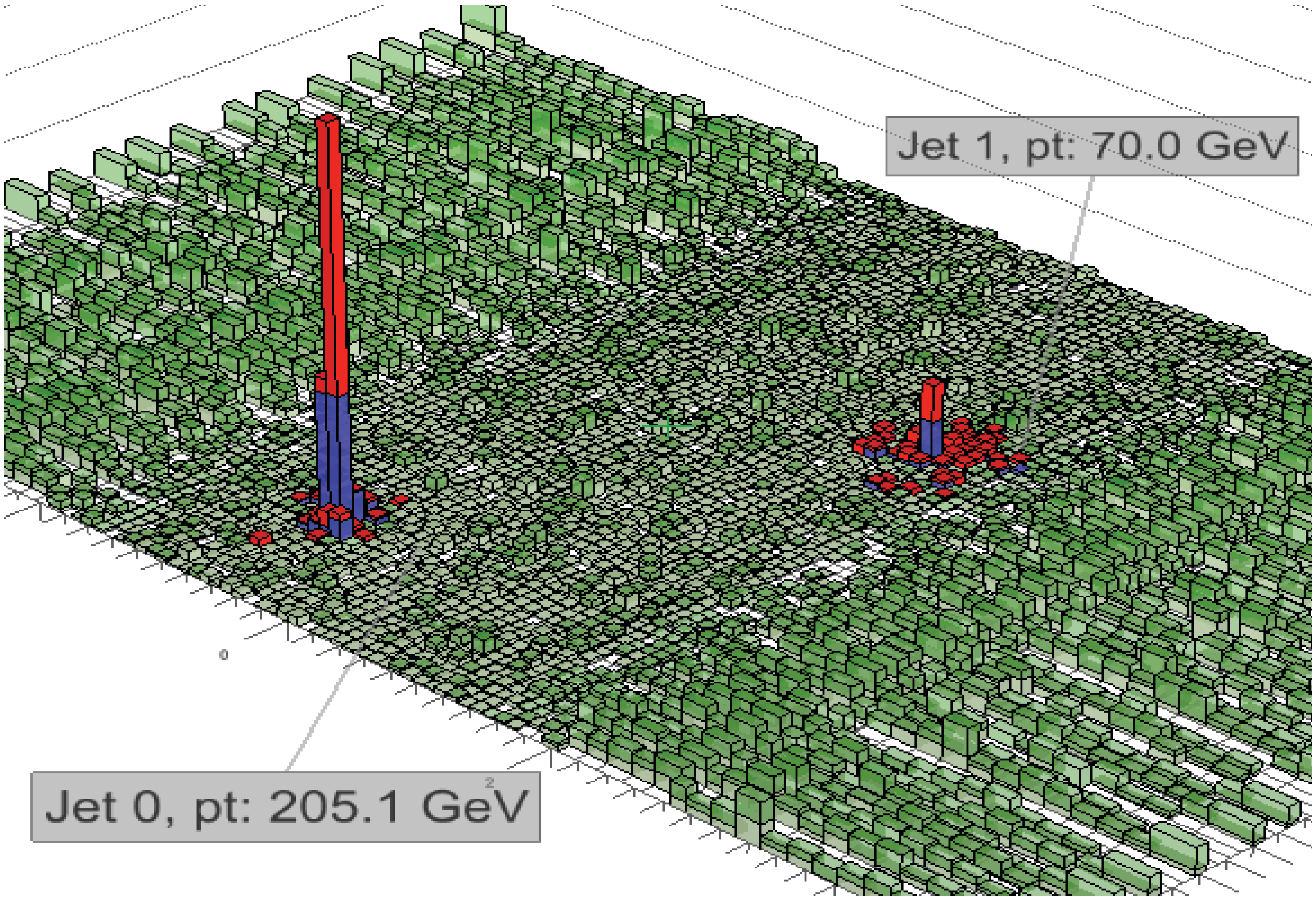
Jet R_{AA}/R_{CP} at the LHC



$R_{CP}^{Jet} \sim R_{AA} \sim 0.5$ (>50 GeV)

No significant p_T and R dependence of R_{CP} for p_T>100 GeV

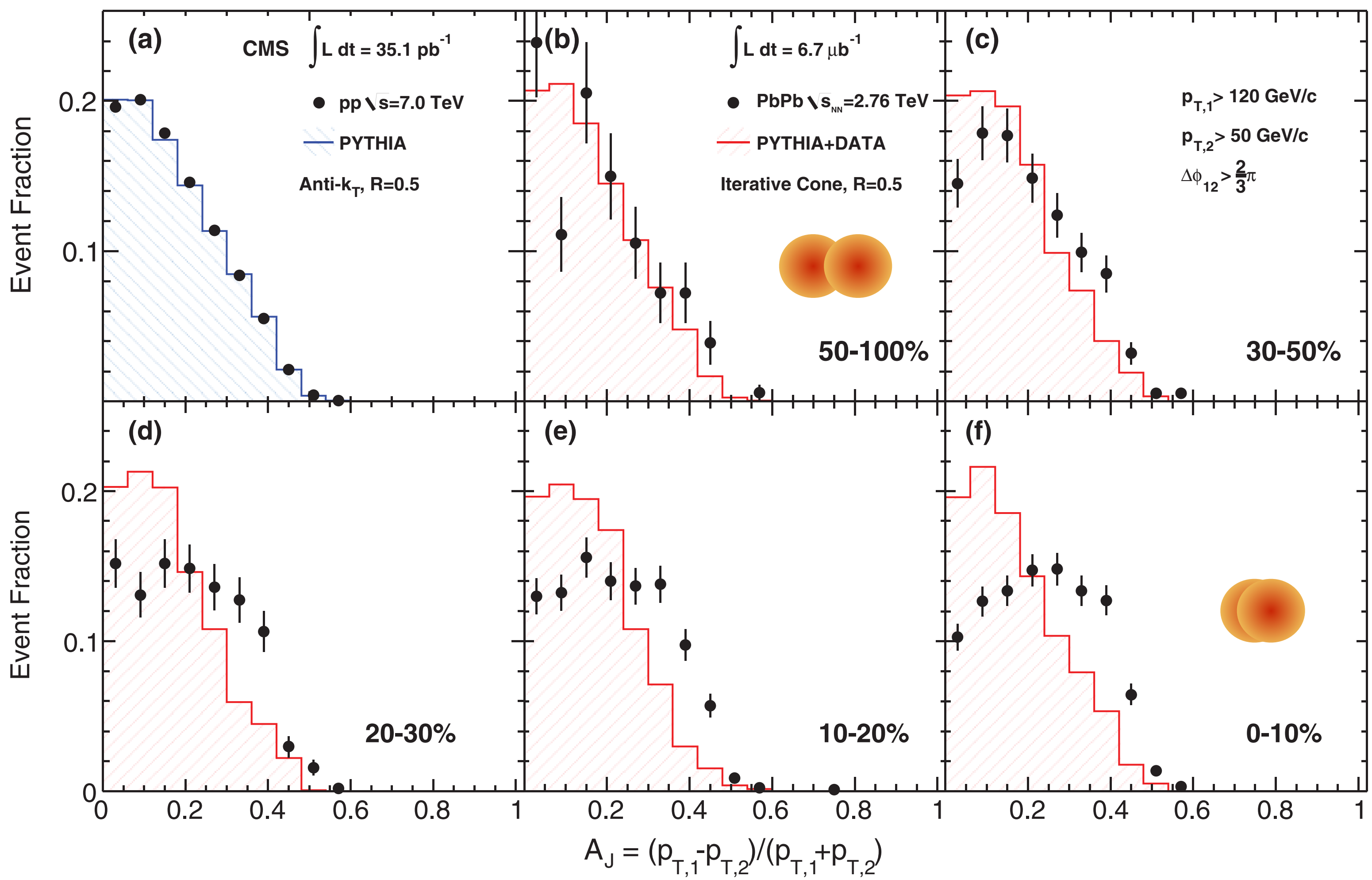
Di-jet Asymmetry/Imbalance A_J



$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

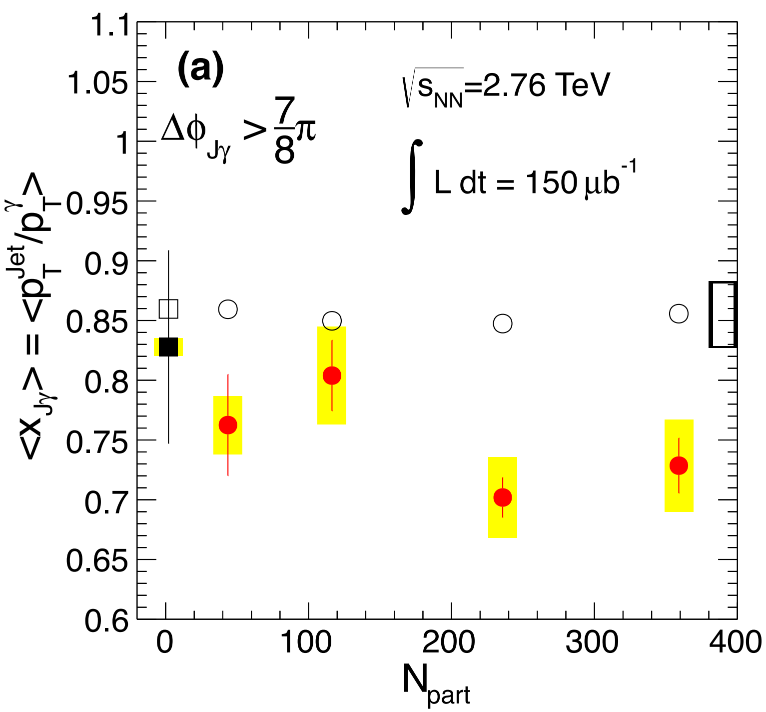
Di-jet Asymmetry/Imbalance A_J

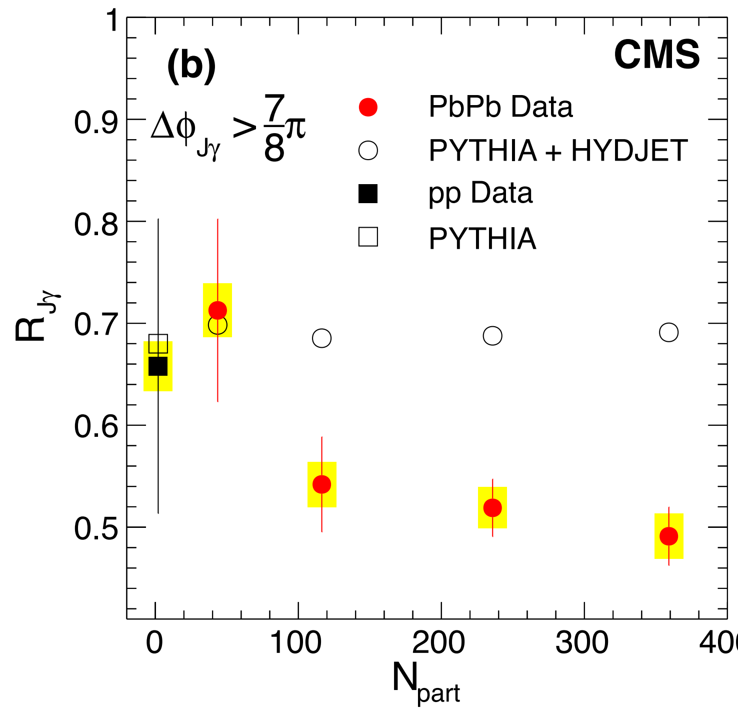
CMS, PRC ***84****, 024906 (2011)*



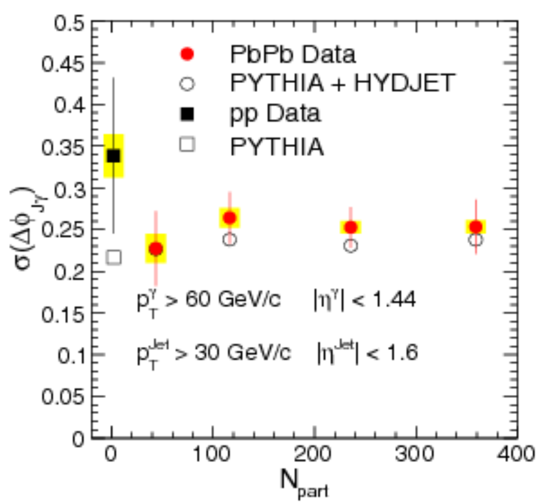
Significant di-jet momentum imbalance A_J observed in central Pb+Pb

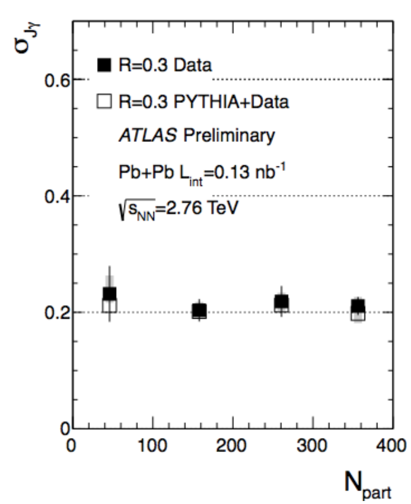
Coincidence Measurements: γ-Jet





p_T^{γ}>60 GeV
p_T^{Jet}>30 GeV



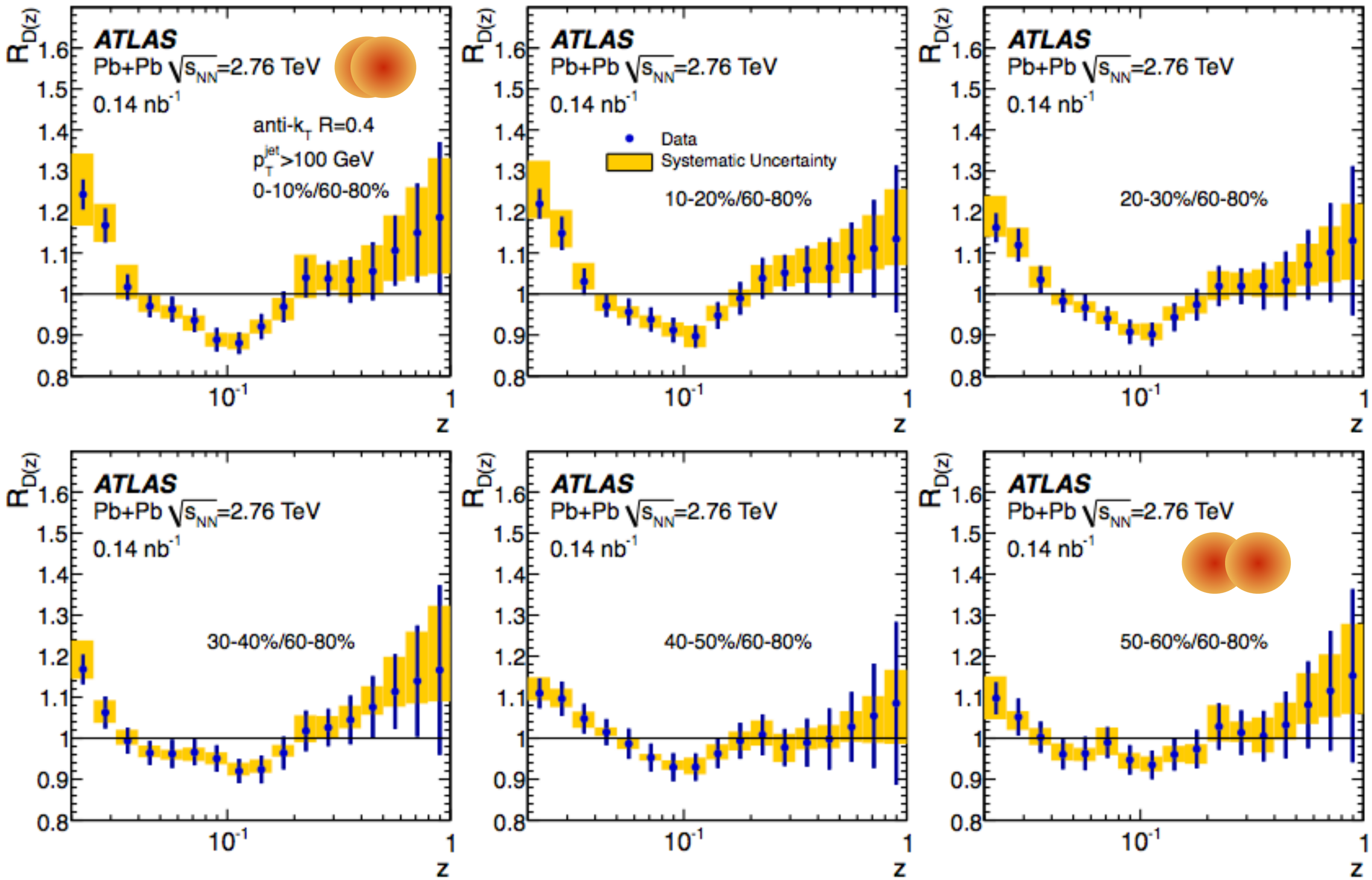


Large quenching effects seen in direct photon measurements

(Consistent with jets measurements? Quark vs. gluon energy loss?)

No angular de-correlation

Jet Softening in Pb-Pb Collisions!?



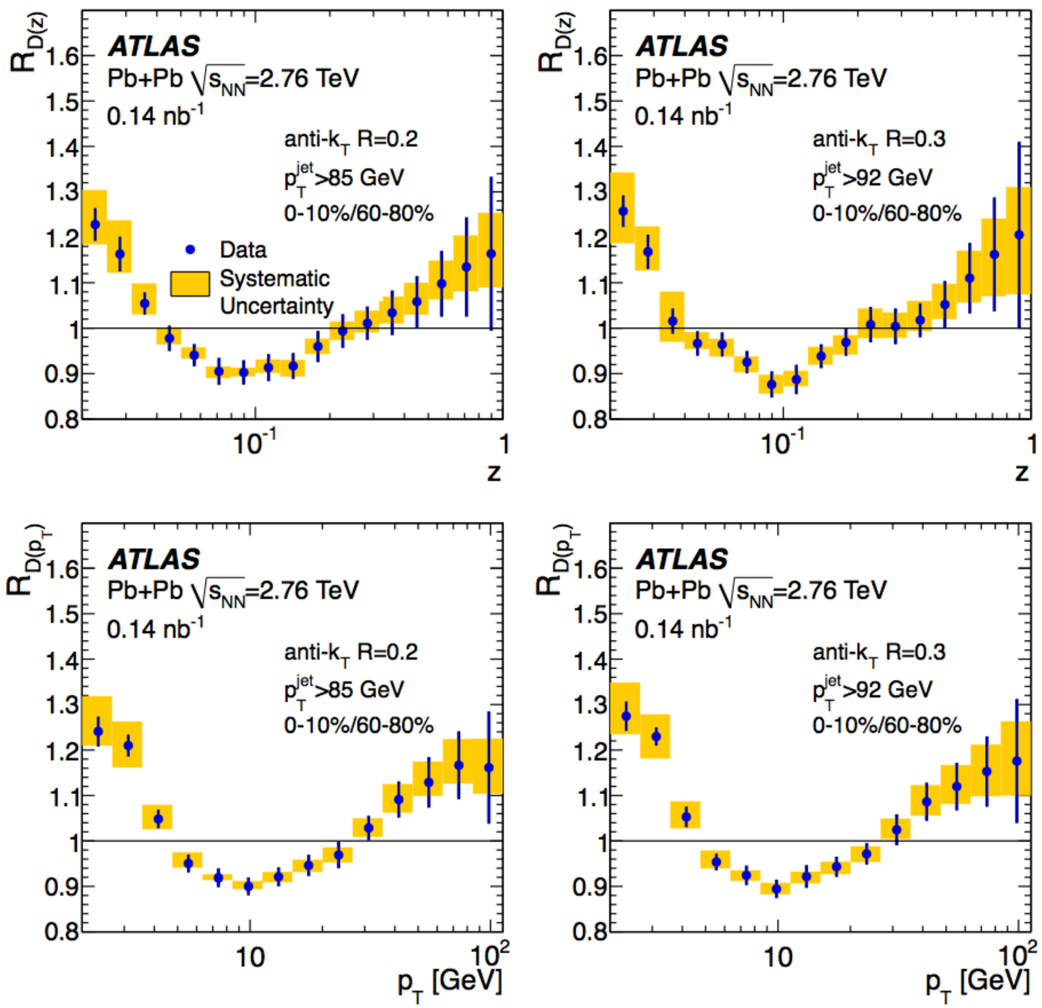
(Small) Enhancement at low z

$$z = \frac{p_T^{hadron}}{p_T^{Jet}}$$

(Moderate) Suppression at intermediate z

No suppression at high z!!!

Jet Softening in Pb-Pb Collisions!?

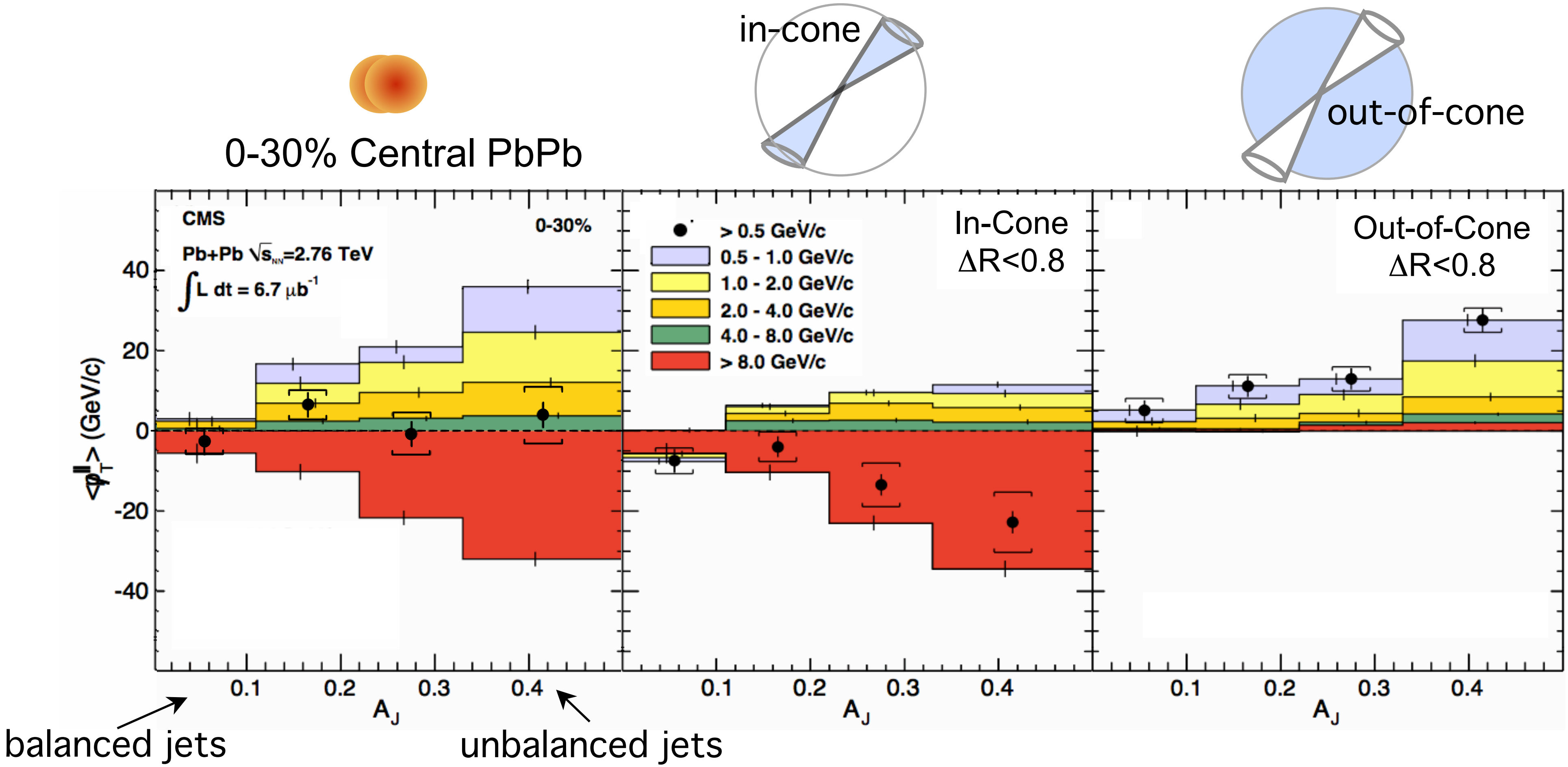


(Small) Enhancement at low z

(Moderate) Suppression at intermediate z

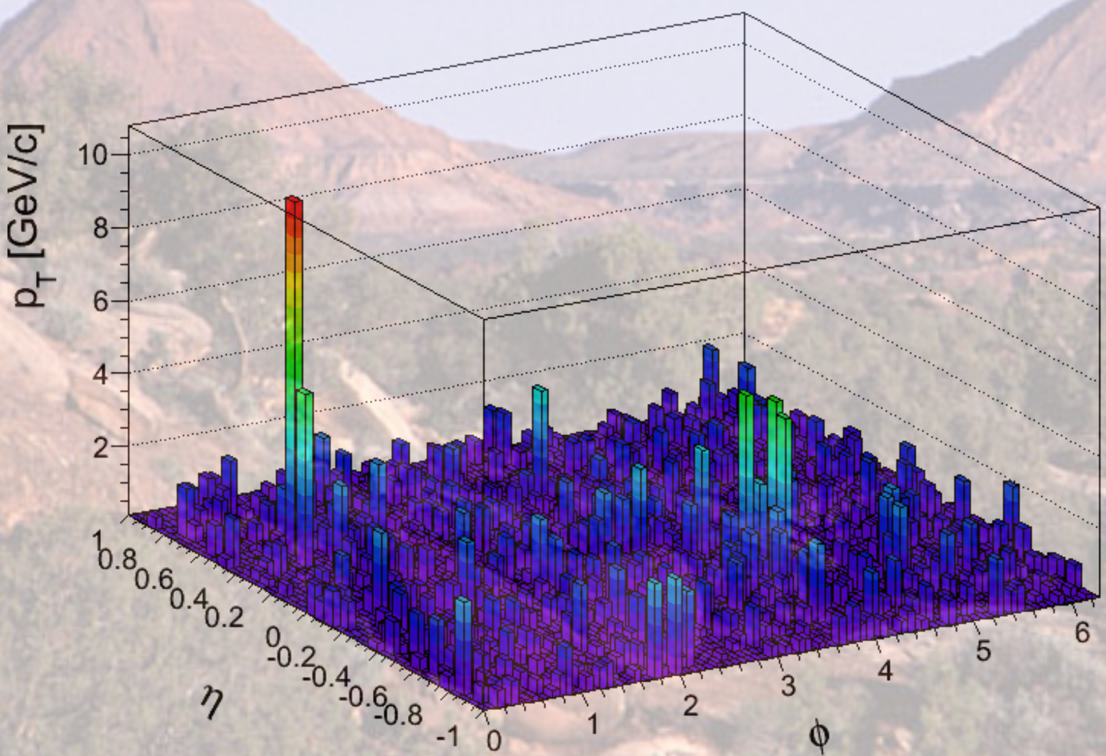
No suppression at high z!!!

Where does the lost energy go at the LHC? Missing $p_T^{||}$

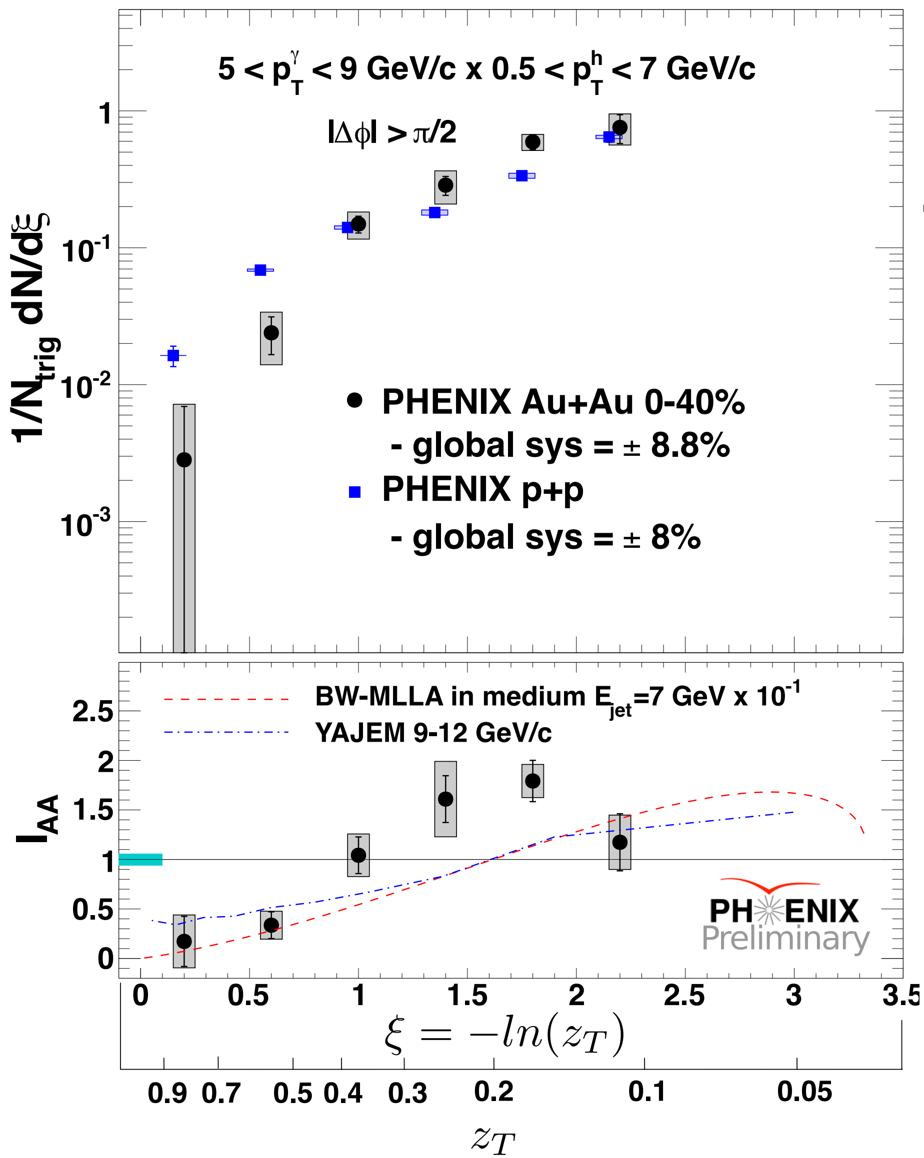


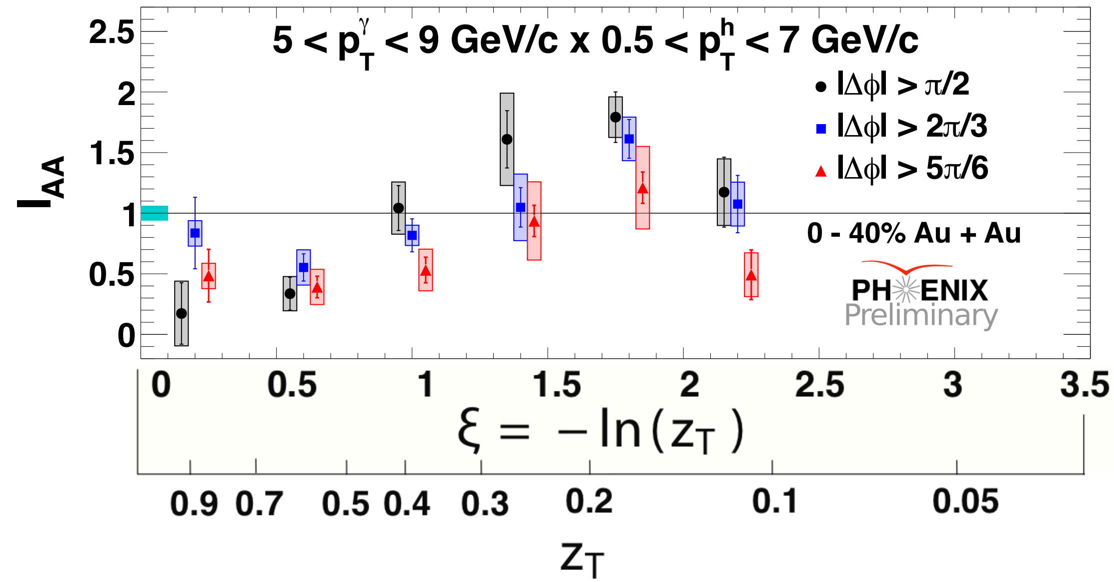
The momentum difference in the di-jet is balanced by low p_T particles at large angles relative to the away side jet axis!

Jet Measurements at RHIC



Jets @ RHIC: γ^{direct}/jet-hadron correlations





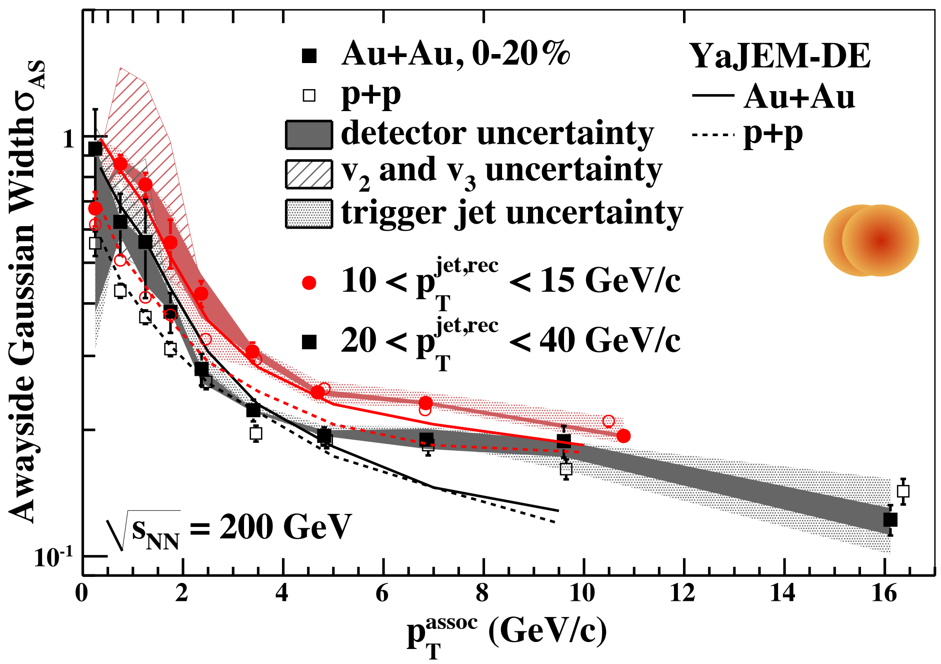
Enhancement at low z

Suppression at high z

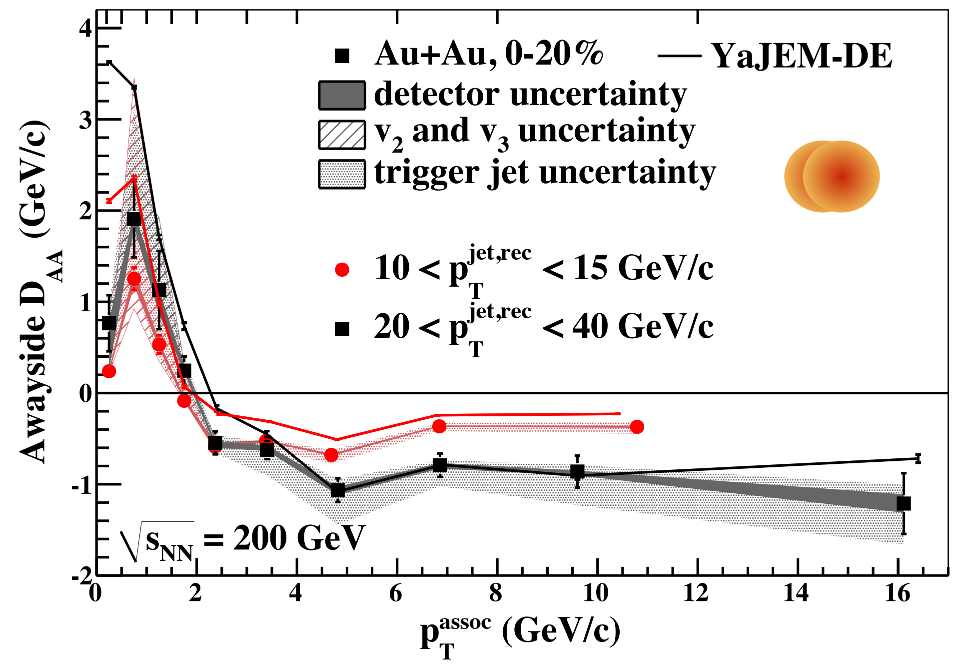
Broadening at low z

Jets @ RHIC: γ^{direct}/jet-hadron correlations

Phys.Rev.Lett. 112 (2014) 12, 122301



Energy difference: AuAu-pp



Jet Broadening at low p_T (large uncertainties due to potential jet v_2/v_3)

Quenched energy at high p_T balanced by low p_T enhancement
↔ Suppression of high-z (enhancement of low-z) particles observed!

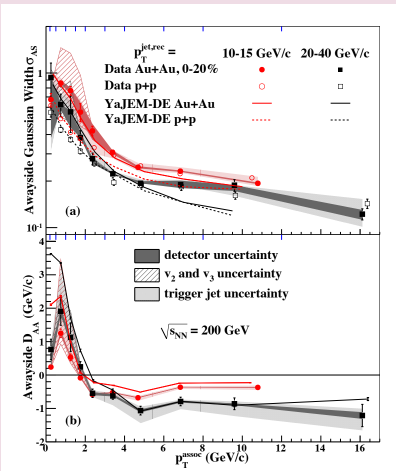
Consistent picture between γ^{direct}/jet-hadron correlations @ RHIC!

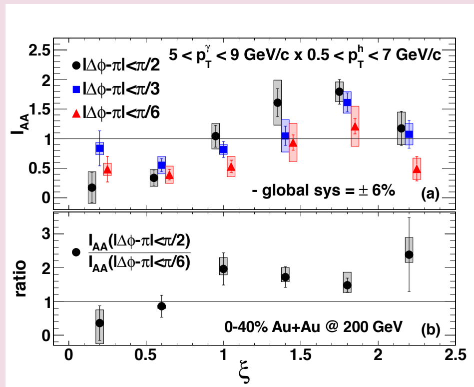
Caveat: Jet-Hadron correlations probe jet structure only statistically!
→ Use fully reconstructed di-jets, direct comparison to LHC!

Current Status: Jet Quenching at RHIC and the LHC

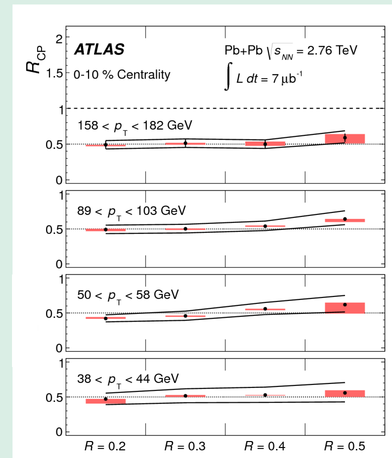
Hot QCD Matter White Paper, arXiv:1502.02730

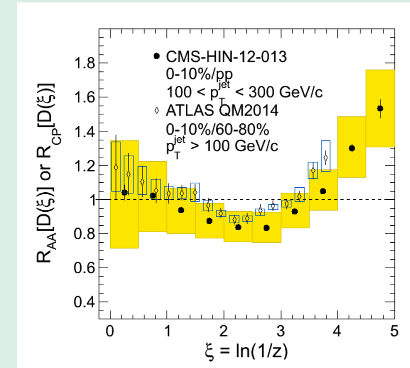
Jets @ RHIC

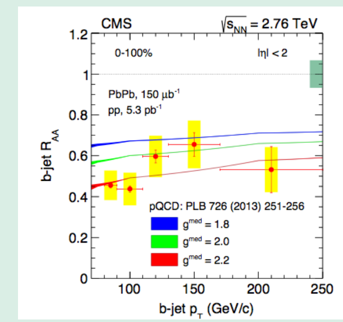


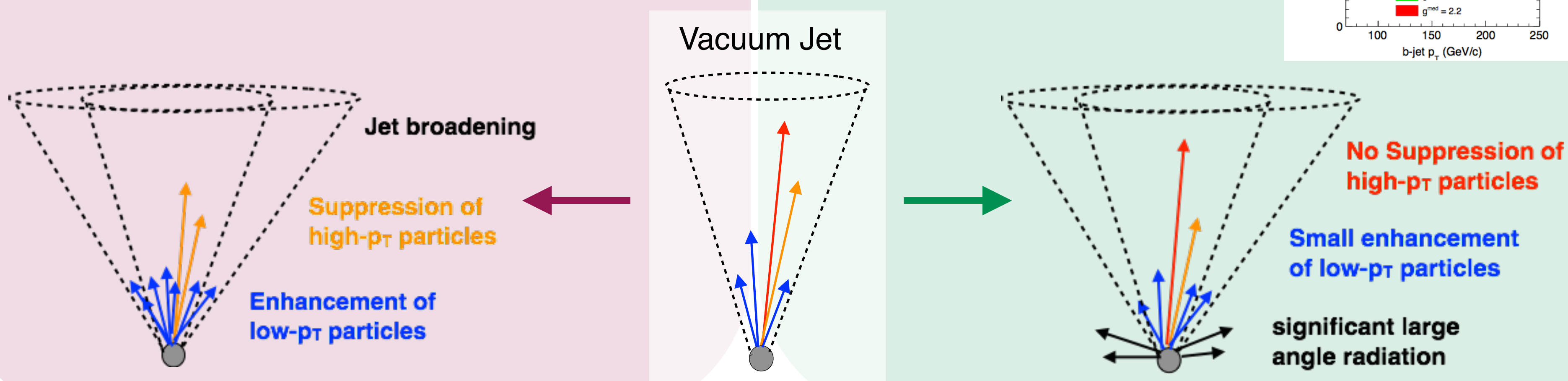


Jets @ LHC









Do we have a consistent picture?

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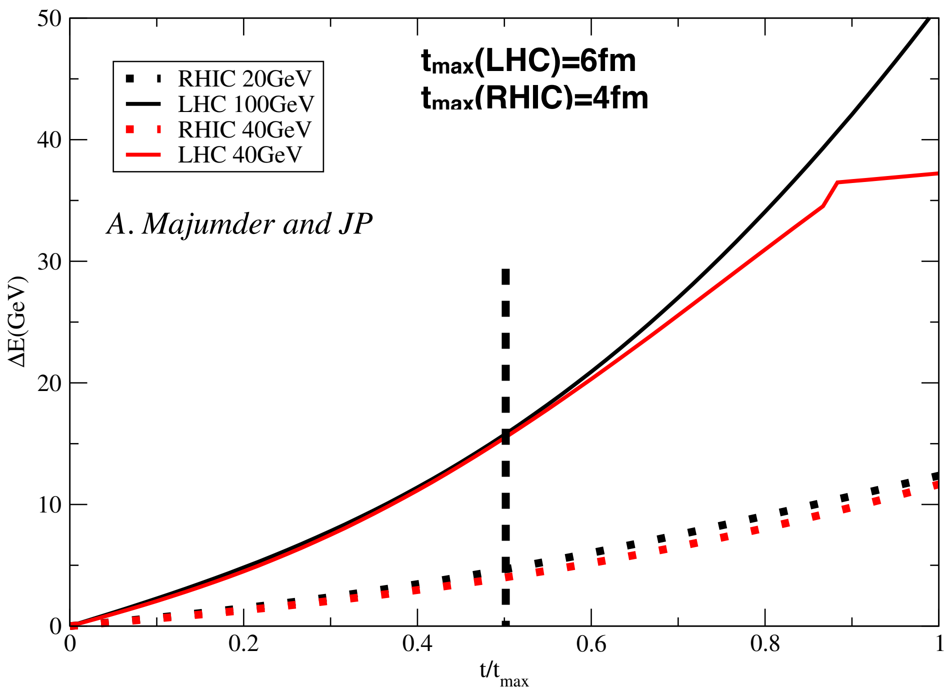
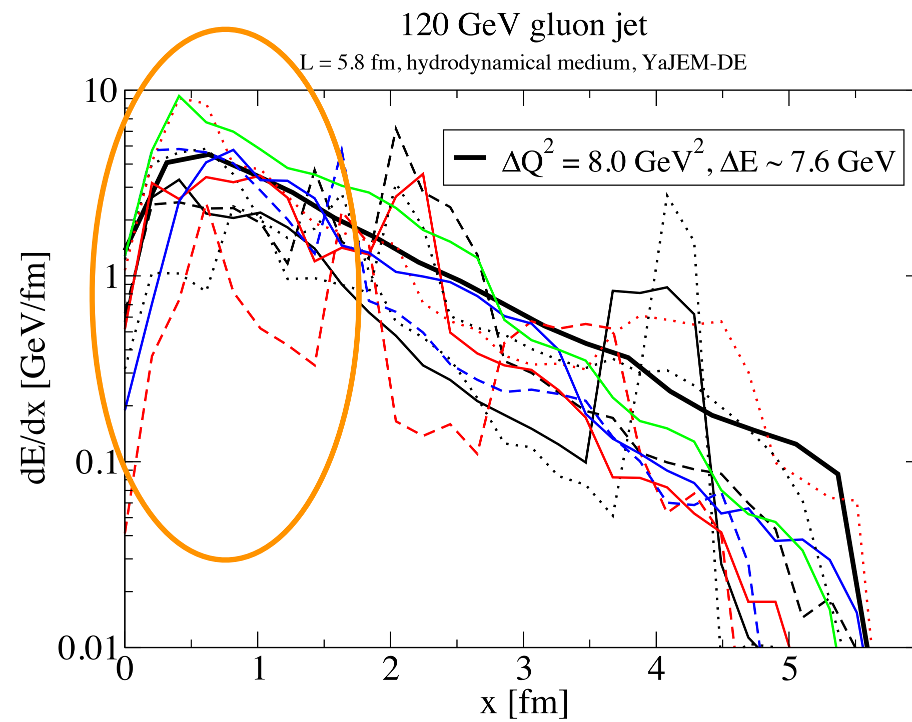
Integrated energy loss (in a brick)





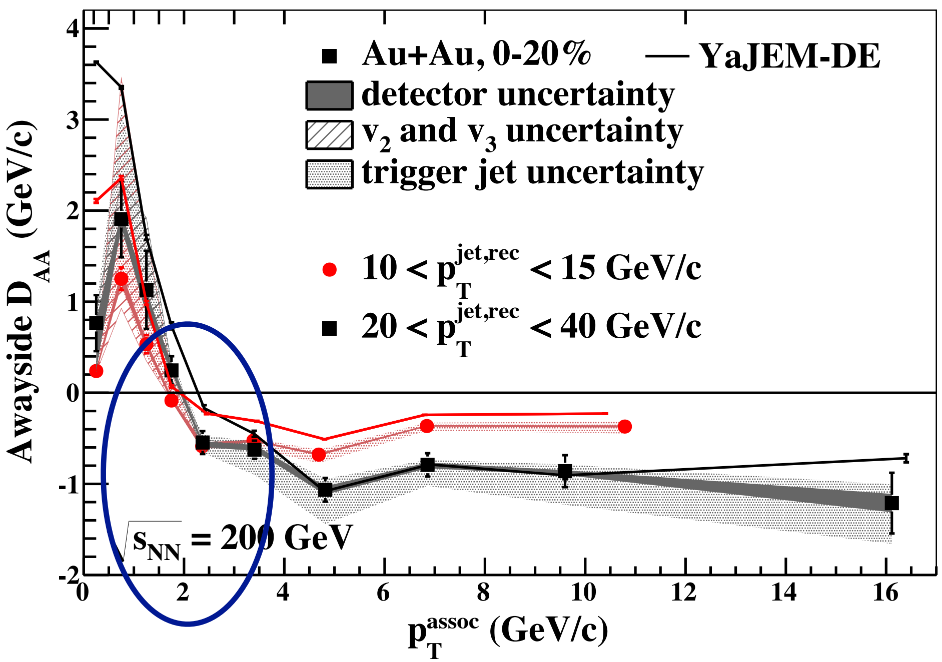
LHC larger energy loss at early times (medium more dense, mainly gluon jets) → diffusion in medium → larger angles

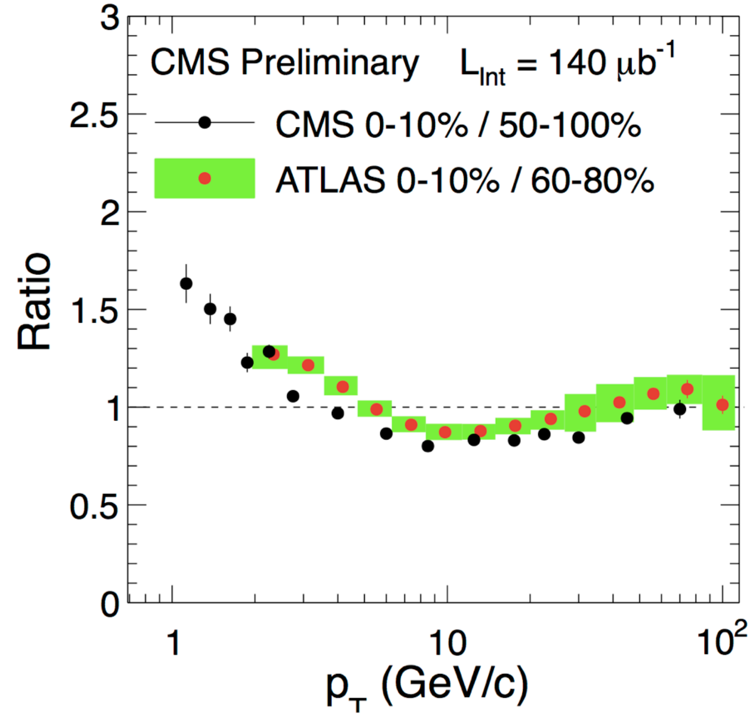
RHIC smaller energy loss at early times (less dense medium, quark jets) → less diffusion in the medium → closer to jet axis

→ Radiative energy loss (pQCD) picture can qualitatively explain the differences RHIC/LHC

Do we have a consistent picture? “Medium-scale” …

Energy difference: AuAu-pp





T. Renk, Phys.Rev. C87 (2013) 2, 024905

Back-of-the-envelope estimate of the scale (T. Renk) given by the typical accumulated medium momentum probed during subsequent interactions: **$P_{med} = L/\lambda\langle P\rangle$**

Typical length **L = 5 fm**; mean-free path **λ = 1 fm** and typical momentum scale in the medium **⟨P ⟩ = 3T** (with the medium temperature **T = 200 MeV**) → **P_{med} ≈ 2-3 GeV for RHIC**

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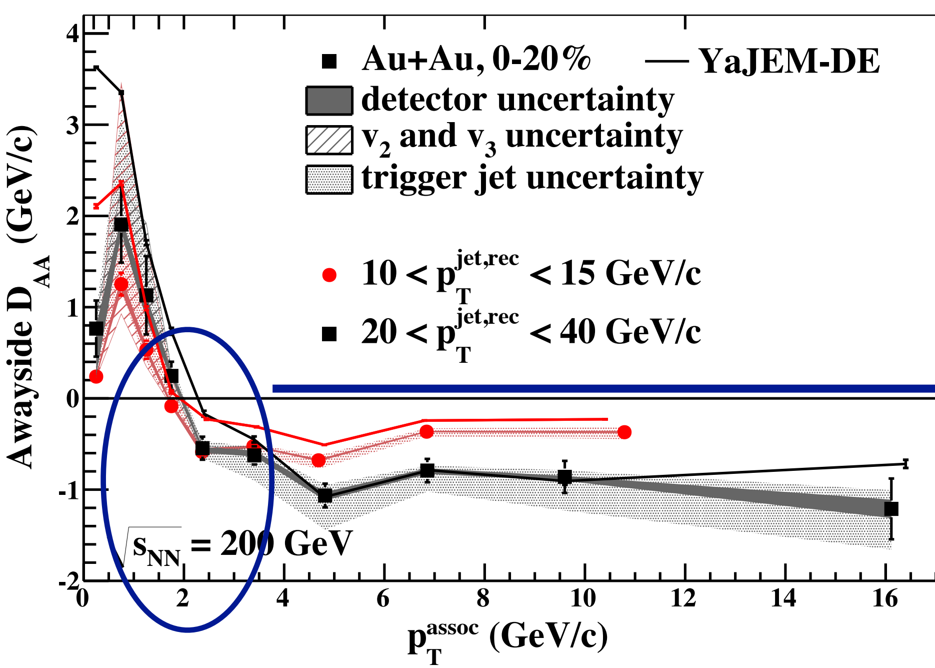

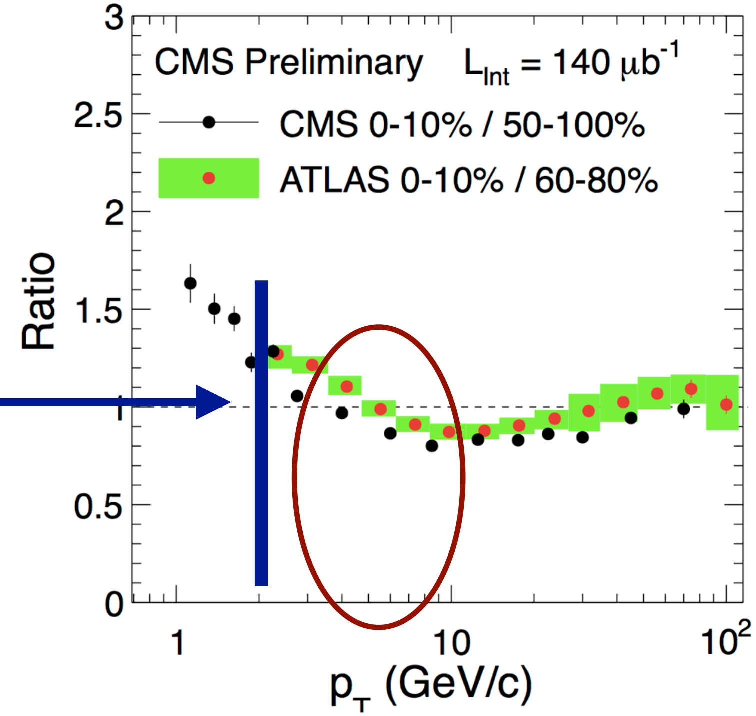

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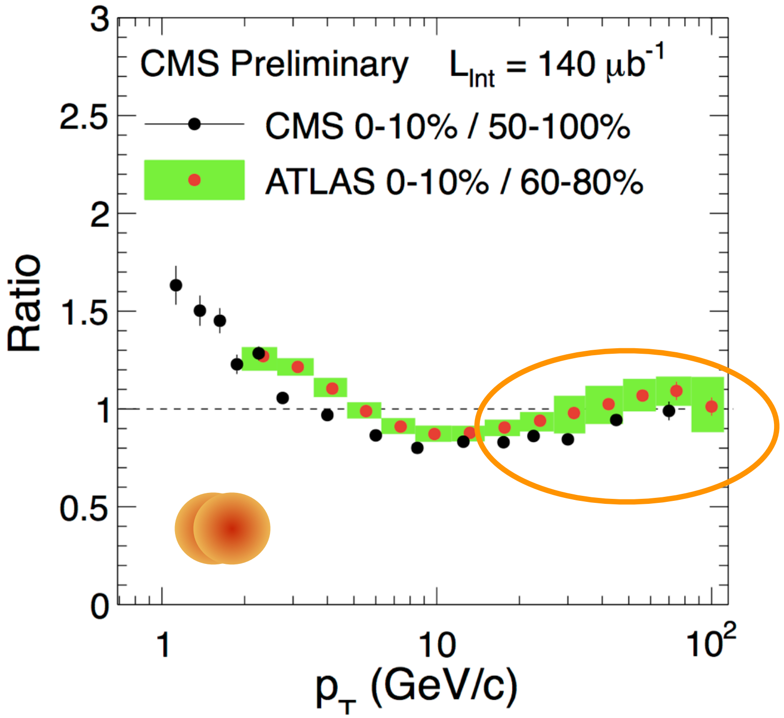
Apparent increase in $P_{med} = L/\lambda\langle P\rangle \approx$ 4-5 GeV at the LHC qualitatively consistent with pQCD arguments!

Do we have a consistent picture? What about the FF at the LHC?



FF ratio @ high z → 1

Consistent with radiative energy loss picture or something new?

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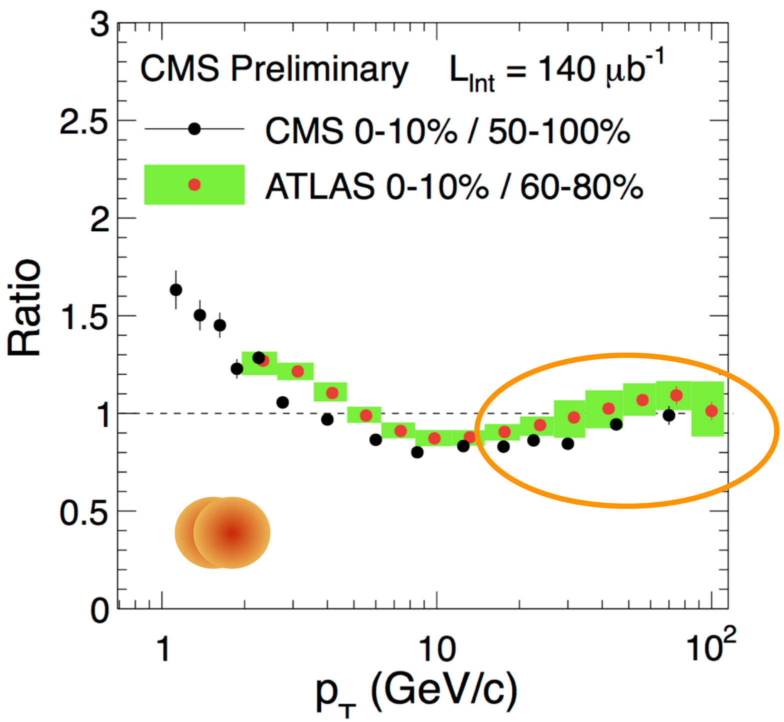

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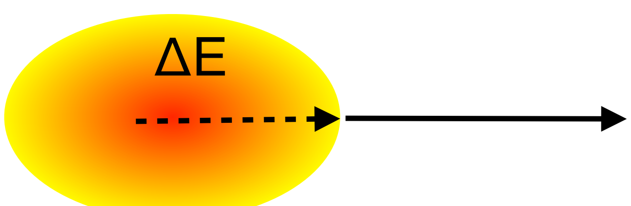
Consistent with radiative energy loss picture or something new?

pp $\longrightarrow$ $E_{Jet}(pp)$

AA 

$E_{Jet}(AA)$

Initial parton energy > $E_{Jet}(AA)$

In FF measurements:

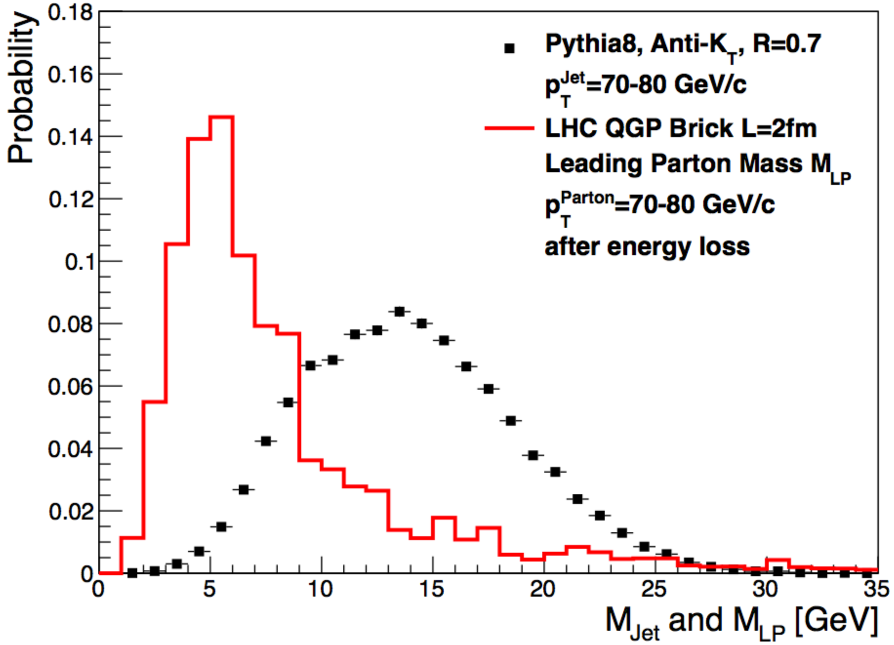
$E_{Jet}(pp) = E_{Jet}(AA)$

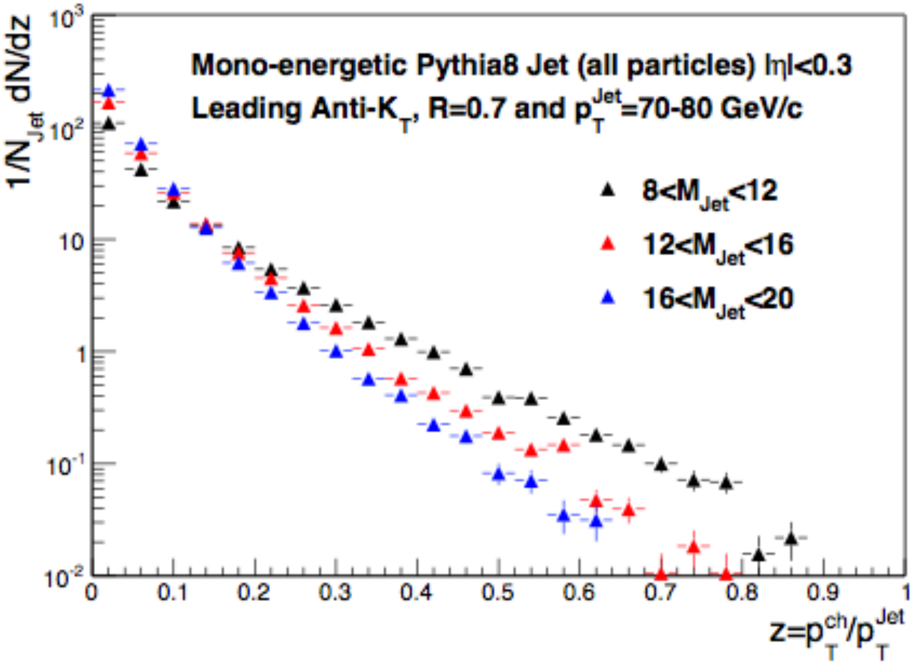
(only small enhancement of jet energy at low-z, few %)

But what about the virtuality of the (leading) parton after energy loss in the medium?

Do we have a consistent picture? Importance of Virtuality …

A. Majumder and JP, arXiv:1408.3403





Comparing jets in AA with pp with the same (reconstructed) energy might not be sufficient: *not comparing apples-with-apples*

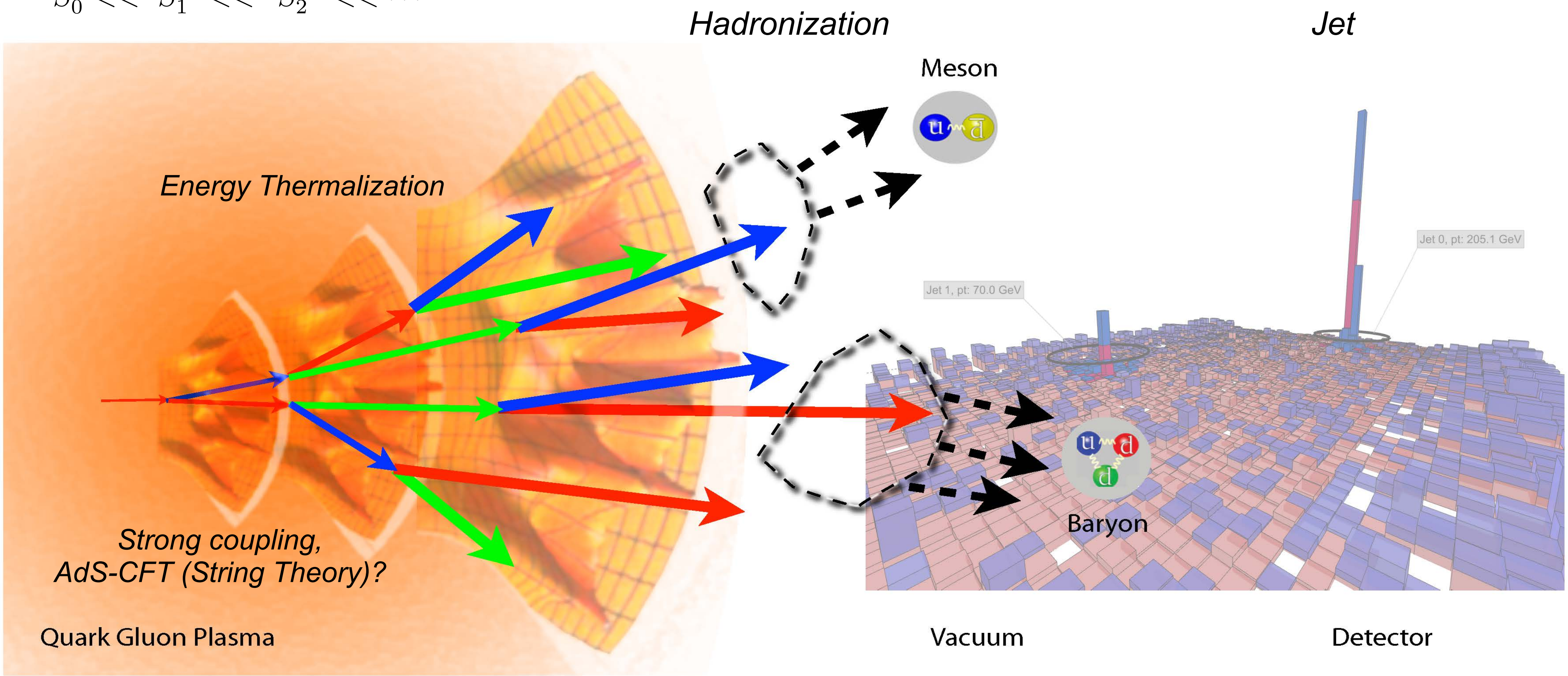
Leading parton after escaping the medium expected to have lower virtuality/jet-mass → will fragment harder wrt pp!

→ Jet Mass measurements at the LHC (and RHIC) necessary …

Jet Quenching in the QGP

perturbative QCD (pQCD, weak coupling)

$$Q_0^2 >> Q_1^2 >> Q_2^2 >> \cdots$$
$$S_0^2 << S_1^2 << S_2^2 << \cdots$$



(Qualitative) Consistent pQCD-type radiative jet energy loss picture

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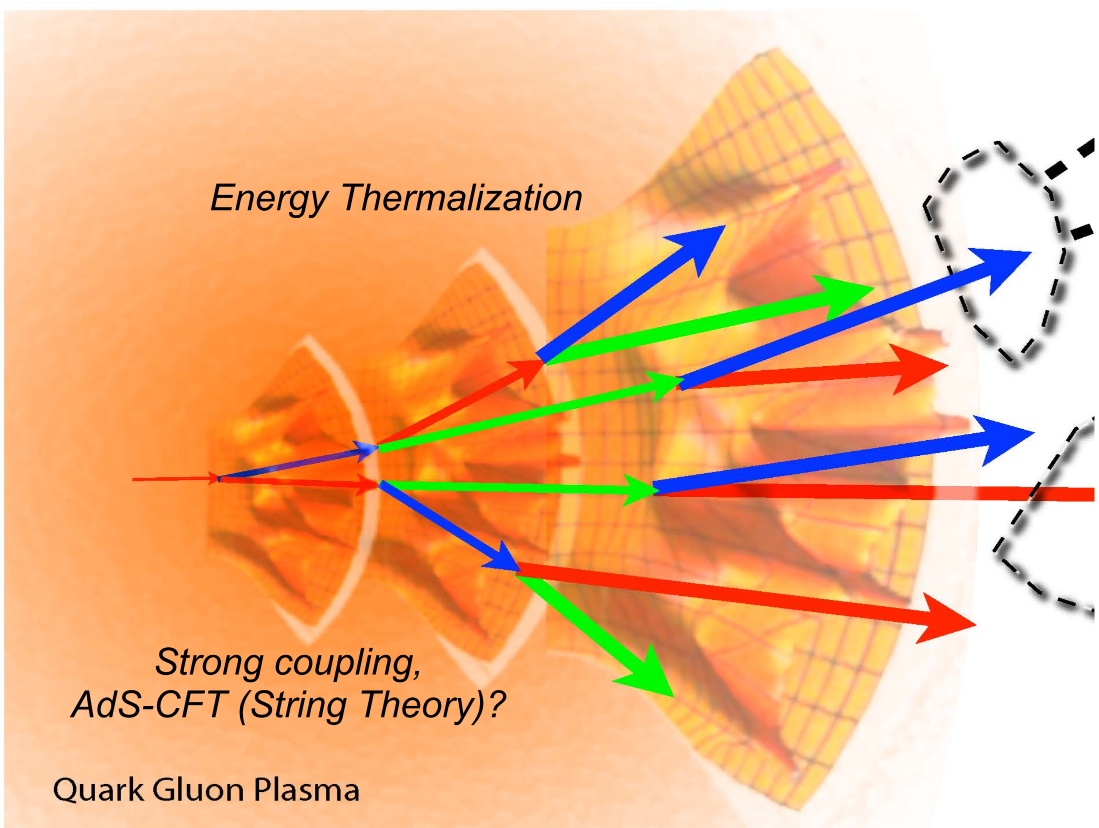


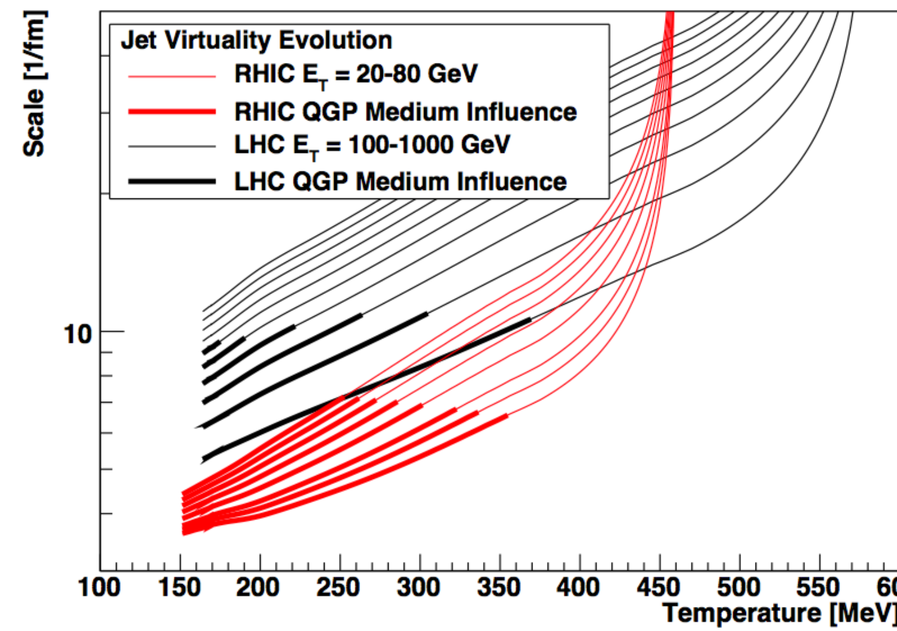


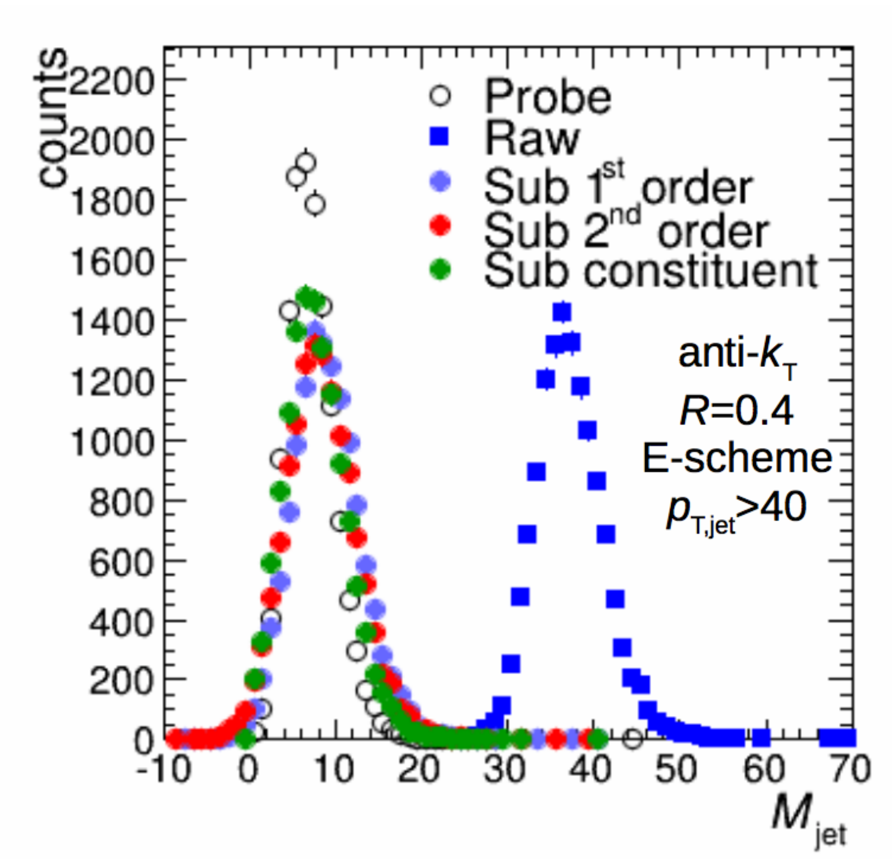
Figure 1.17: Scale probed in the medium in [1/fm] via high energy partons as a function o the local temperature in the medium. The red (black) curves are for different initial parton energies in the RHIC (LHC) medium.

(Qualitative) Consistent pQCD-type radiative jet energy loss picture

→ Jets (via their virtuality evolution) probe the QGP over a wide range of length scales; *Jets are QGP microscopes*!

Jet Mass/Virtuality Measurements in Heavy-Ion Collisions

$$M_{Jet} = \sqrt{E^2_{Jet} - p^2_{Jet}} \propto Virtuality$$



Jet shape derivative method (area based):
Soyez et al. arXiv:1211.2811

Constituent subtraction:
Berta et al. arXiv:1403.3108

Talk by A. Majumder yesterday

Type I: which quantify how the medium changes the jet

$$\hat{q}(E,Q^2) \qquad \hat{q}_4(E,Q^2) = \frac{\langle p_T^4 \rangle - \langle p_T^2 \rangle^2}{L} \ldots$$

$$\hat{e}(E,Q^2) \qquad \hat{e}_2(E,Q^2) = \frac{\langle \delta E^2 \rangle}{L} \qquad \hat{e}_4(E,Q^2) = \frac{\langle \delta E^4 \rangle - \langle \delta E^2 \rangle^2}{L} \ldots$$

Experimental access to virtuality via Jet Mass M_{Jet} measurements
→ Adds a new dimension: E and Q^2

Allows more differential jet quenching measurements as function of E and Q^2: For example fragmentation functions, radial profile, …

→ Strong constraints on models!

Soft Drop on One Slide

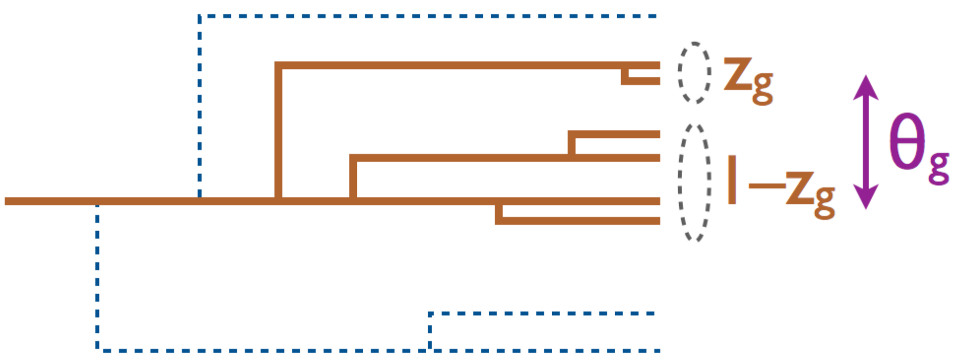
Soft Drop Condition:

$$z > z_{\text{cut}}\, \theta^{\beta}$$

energy threshold

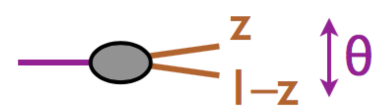
angular exponent

Recursively drop wide-angle soft radiation



Based on declustering an angular-ordered tree

Final jet looks like QCD splitting function



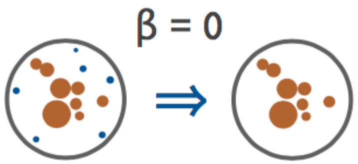
$$\int \frac{d\theta}{\theta}\, dz\, P(z)$$

AP splitting function

β parameter gives nice handle

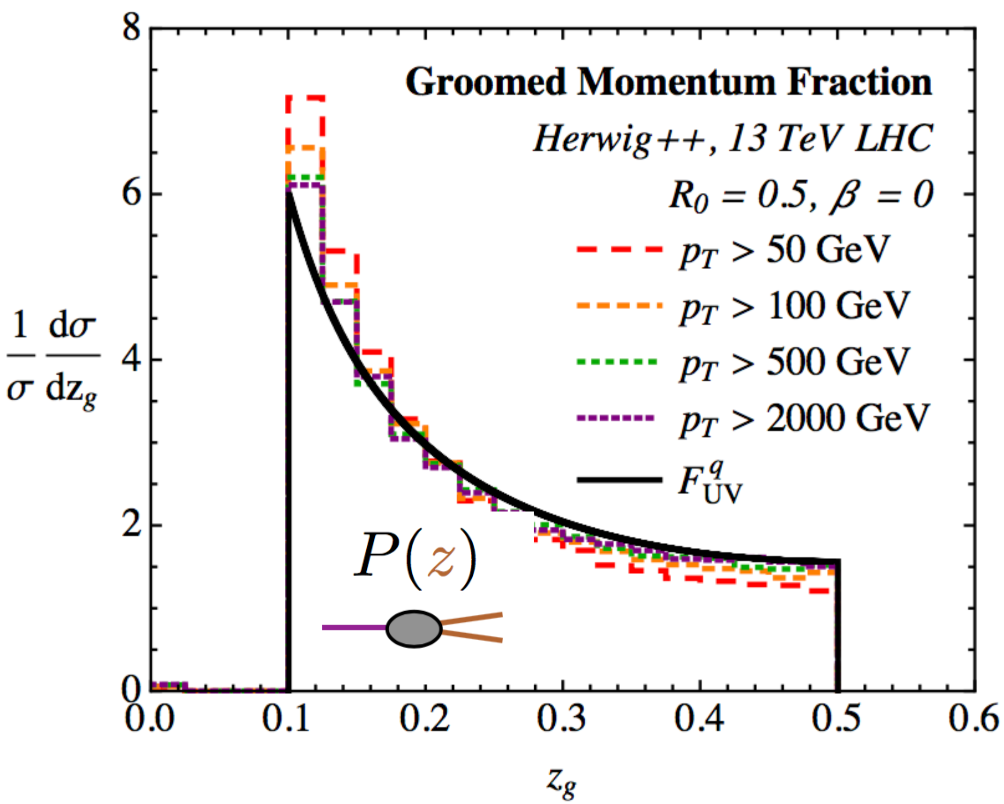
[Larkoski, Marzani, Soyez, JDT, 1402.2657]
[see also Butterworth, Davison, Rubin, Salam, 0802.2470; Dasgupta, Fregoso, Marzani, Salam, 1307.0007]

Measuring the QCD Splitting Function ("Sub-Jets")



$$z > z_{\mathrm{cut}}$$

$$\frac{1}{\sigma}\frac{d\sigma}{dz_g} = \frac{\overline{P}_i(z_g)}{\int_{z_{\mathrm{cut}}}^{1/2} dz\, \overline{P}_i(z)} + \ldots$$



~ independent of α_s

~ independent of jet p_T (>30 GeV)

~ same for quark and gluon

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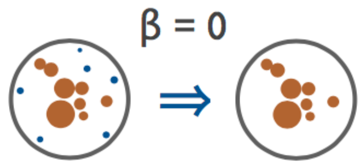

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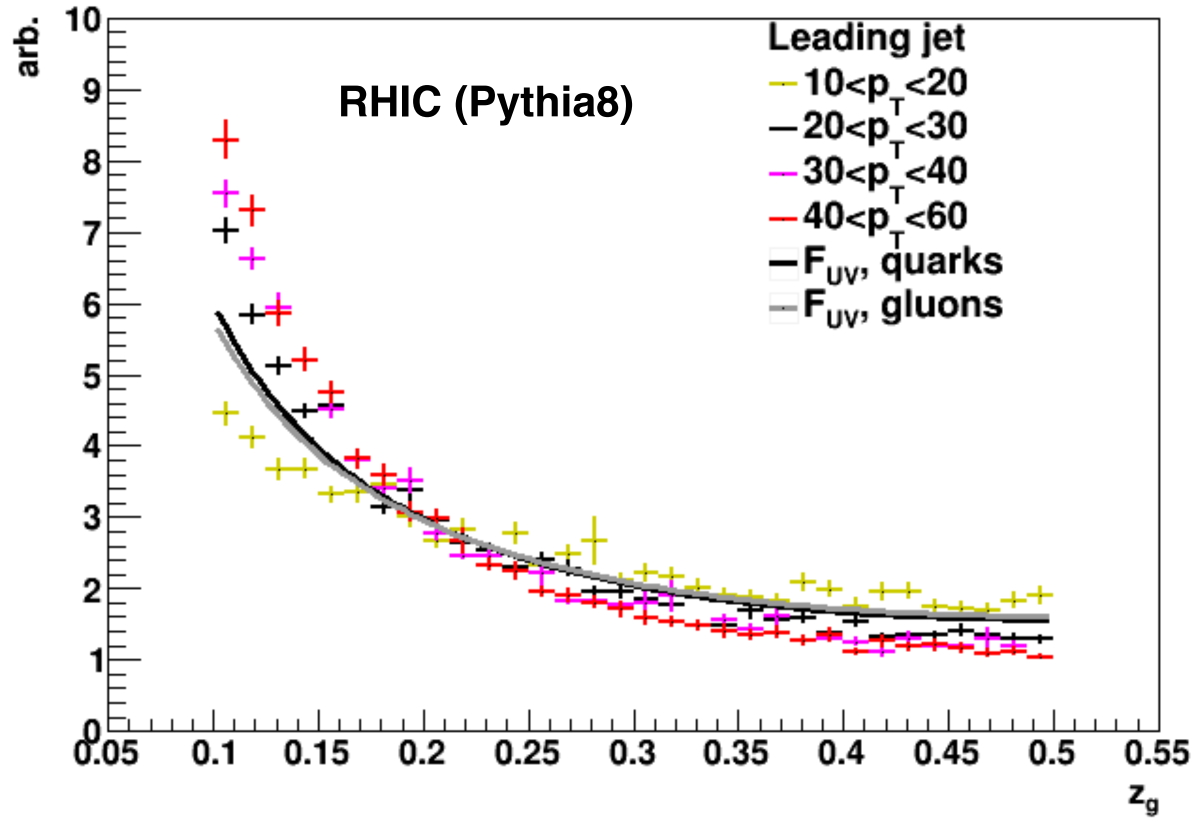

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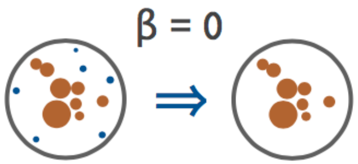
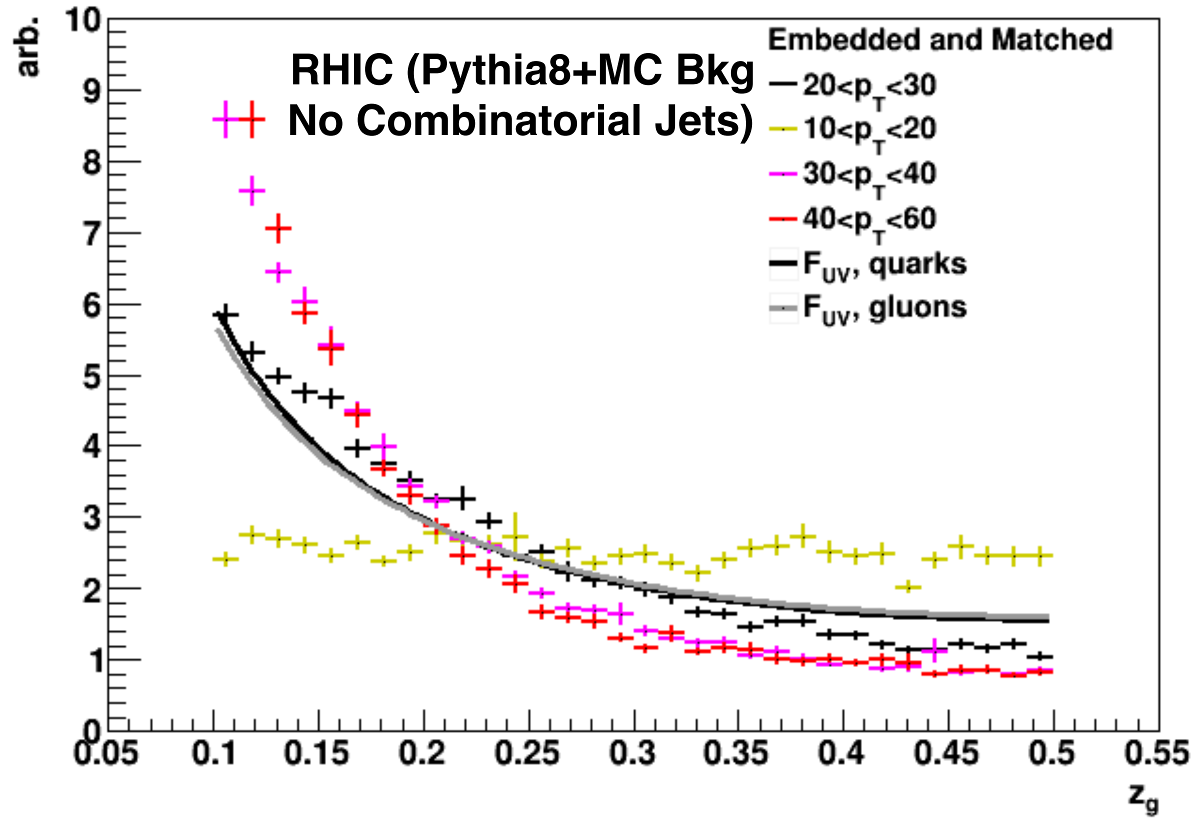


$z > z_{\rm cut}$

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}z_g} = \frac{\overline{P}_i(z_g)}{\int_{z_{\rm cut}}^{1/2} dz\, \overline{P}_i(z)} \quad + \ldots$$



~ independent of α_s

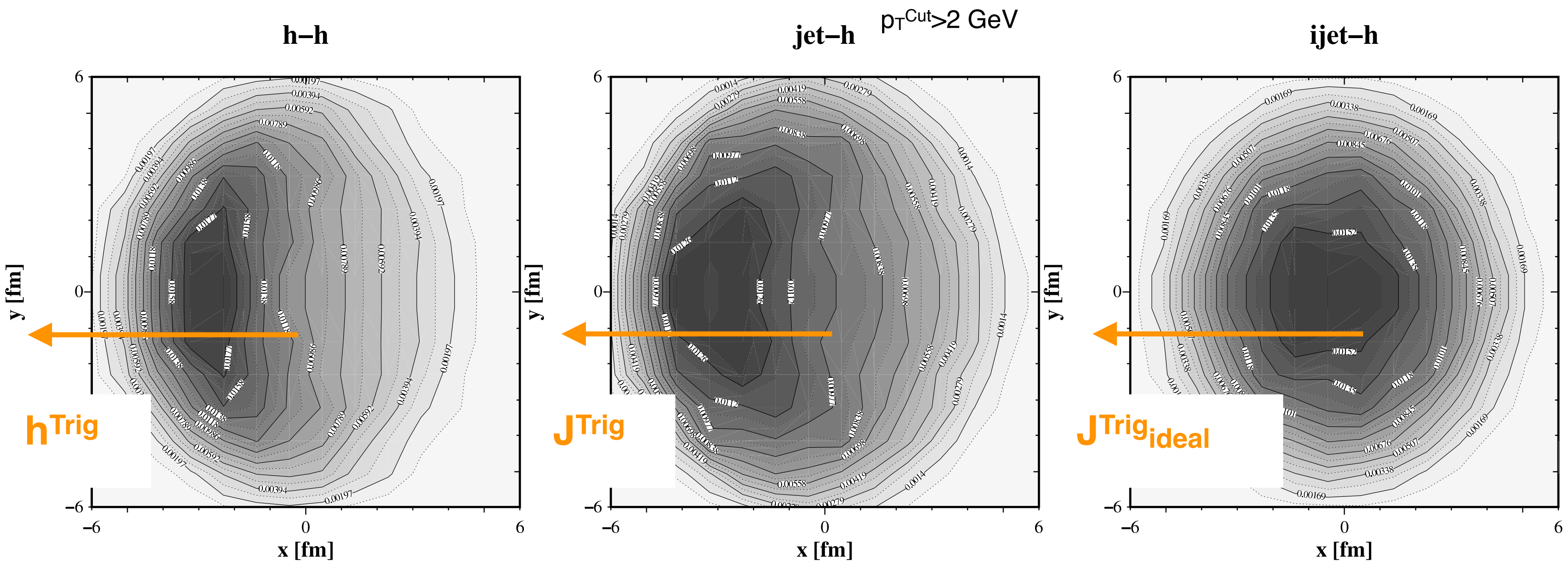
~ independent of jet p_T (>30 GeV)

~ same for quark and gluon

Effect of bkg. fluctuations in z_g suppressed wrt to other sub-jet measurement
→ Good variable for HI!

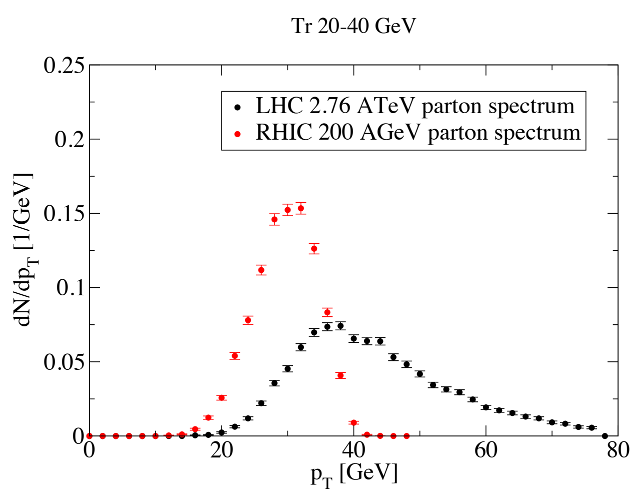
The Role of *Biases: Jet-Geometry-Engineering*

*T. Renk, PRC **87** (2013) 024905 and PRC **88** (2013) 054902*



Biases **(p_T^{Cut}, R, ...) can be used to change *systematically* the *pathlength* of the recoil jet (even more when also applied on recoil jet definition)**

→ Jet-Geometry-Engeneering



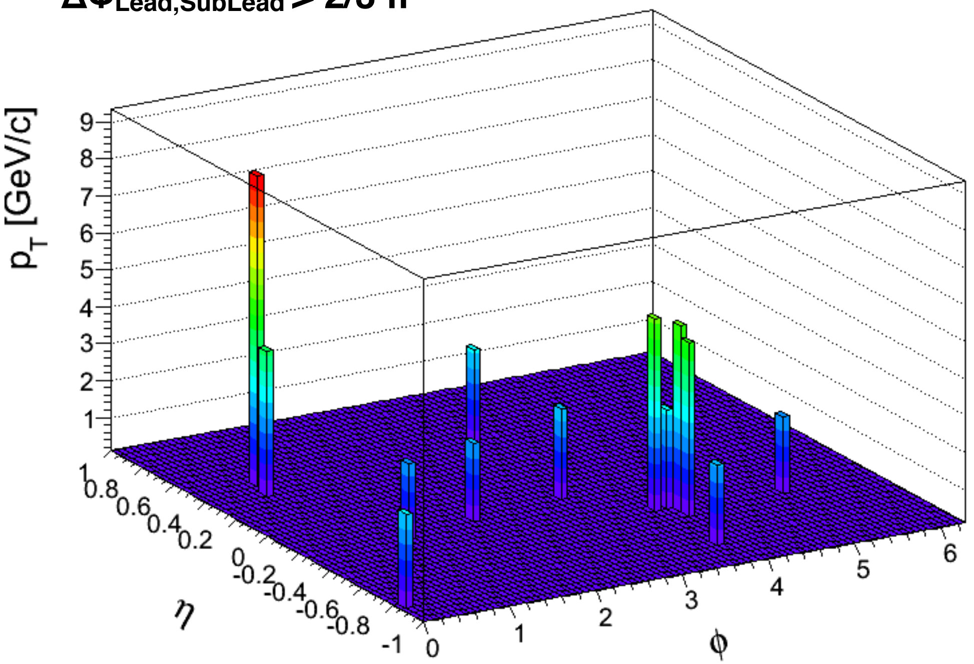
<u>Further *advantage* at RHIC:</u>

Steeply falling spectrum at RHIC

→ good correlation *initial parton energy*

First (biased) Di-Jet Imbalance (A_J) Measurements at RHIC

$p_{T,cut}$=2 GeV/c
p_T^{Lead}>20 GeV
$p_T^{SubLead}$>10 GeV
$\Delta\Phi_{Lead,SubLead}$ > 2/3 π



Calculate A_j with constituent $p_{T,cut}$>2 GeV/c

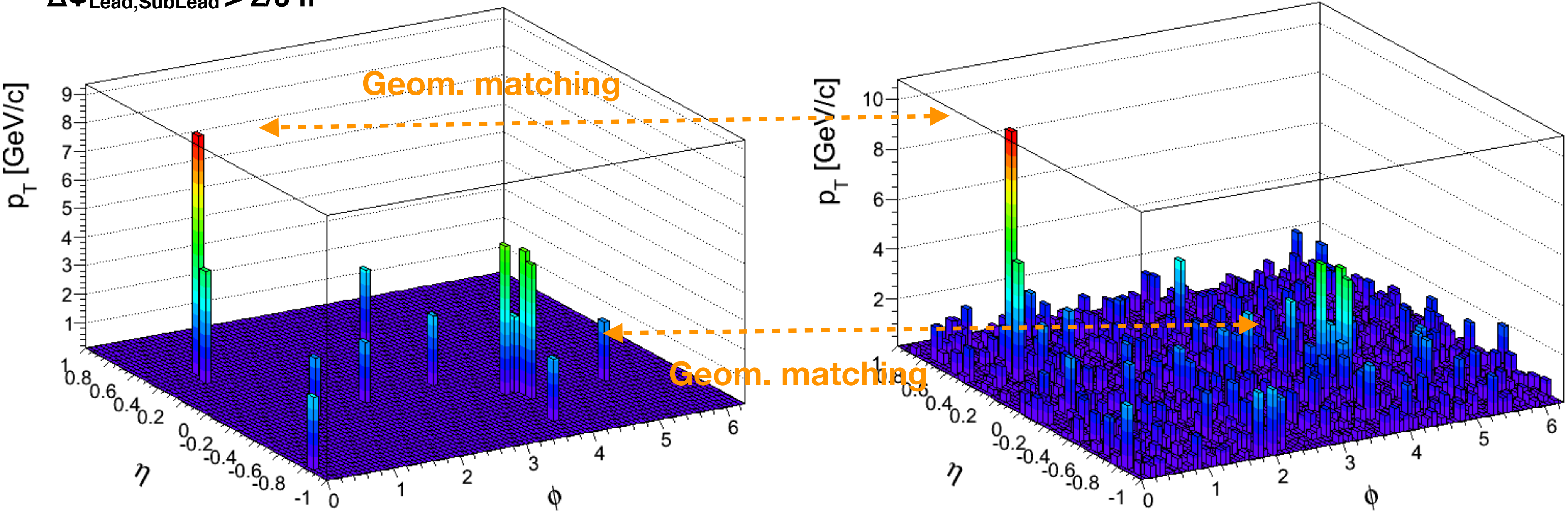
$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}} \qquad p_T = p_T^{rec} - \rho \times A$$

First (biased) Di-Jet Imbalance (A_J) Measurements at RHIC

$p_{T,cut}$=2 GeV/c
p_T^{Lead}>20 GeV
$p_T^{SubLead}$>10 GeV
$\Delta\Phi_{Lead,SubLead}$ > 2/3 π

Rerun jet-finding algorithm anti-k_T on these events ...

$p_{T,cut}$=0.2 GeV/c
p_T^{Lead}>20 GeV ($p_{T,cut}$=2 GeV/c)
$p_T^{SubLead}$>10 GeV ($p_{T,cut}$=2 GeV/c)

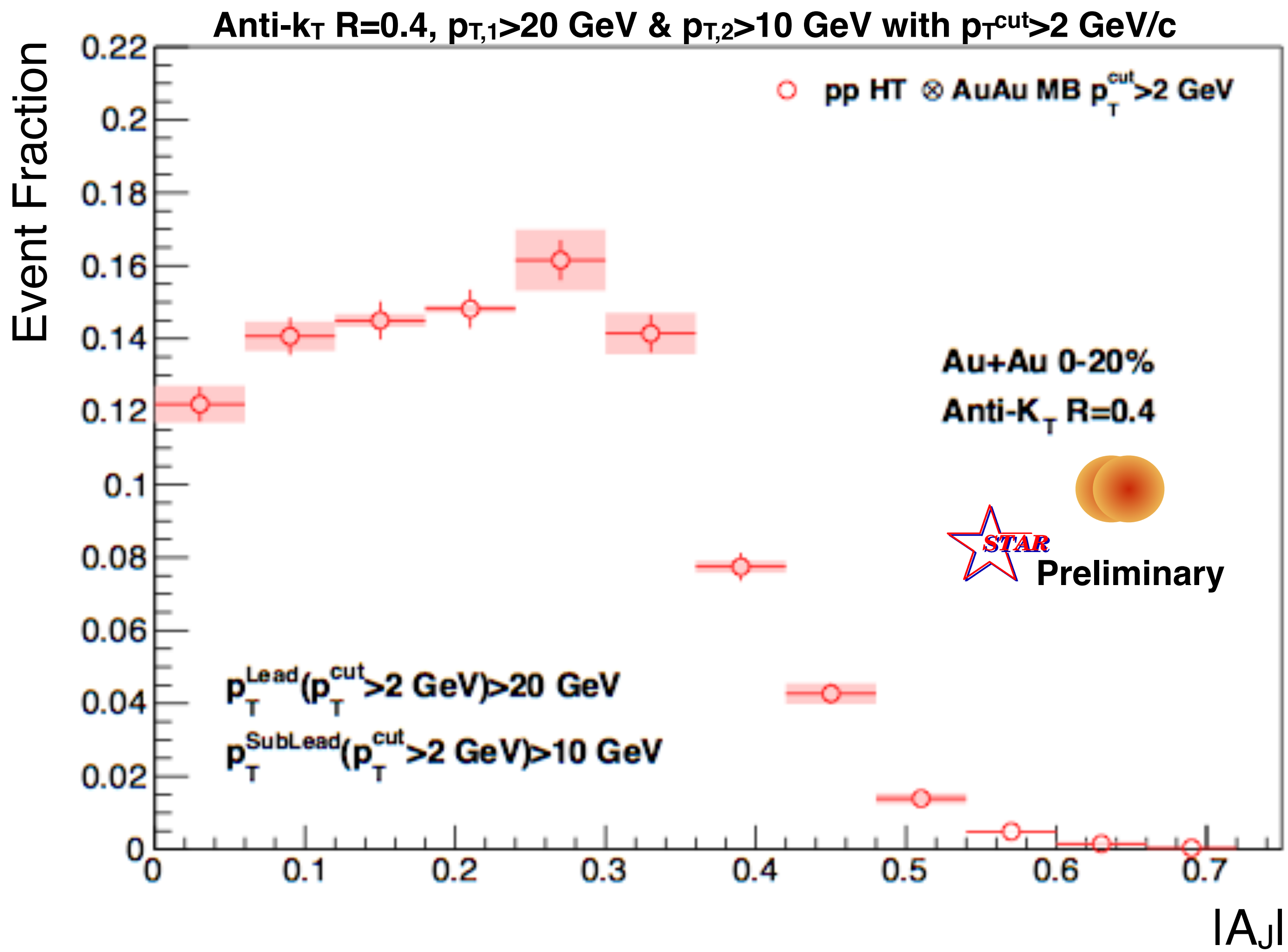


Calculate A_j with constituent $p_{T,cut}$>2 GeV/c

$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}} \qquad p_T = p_T^{rec} - \rho \times A$$

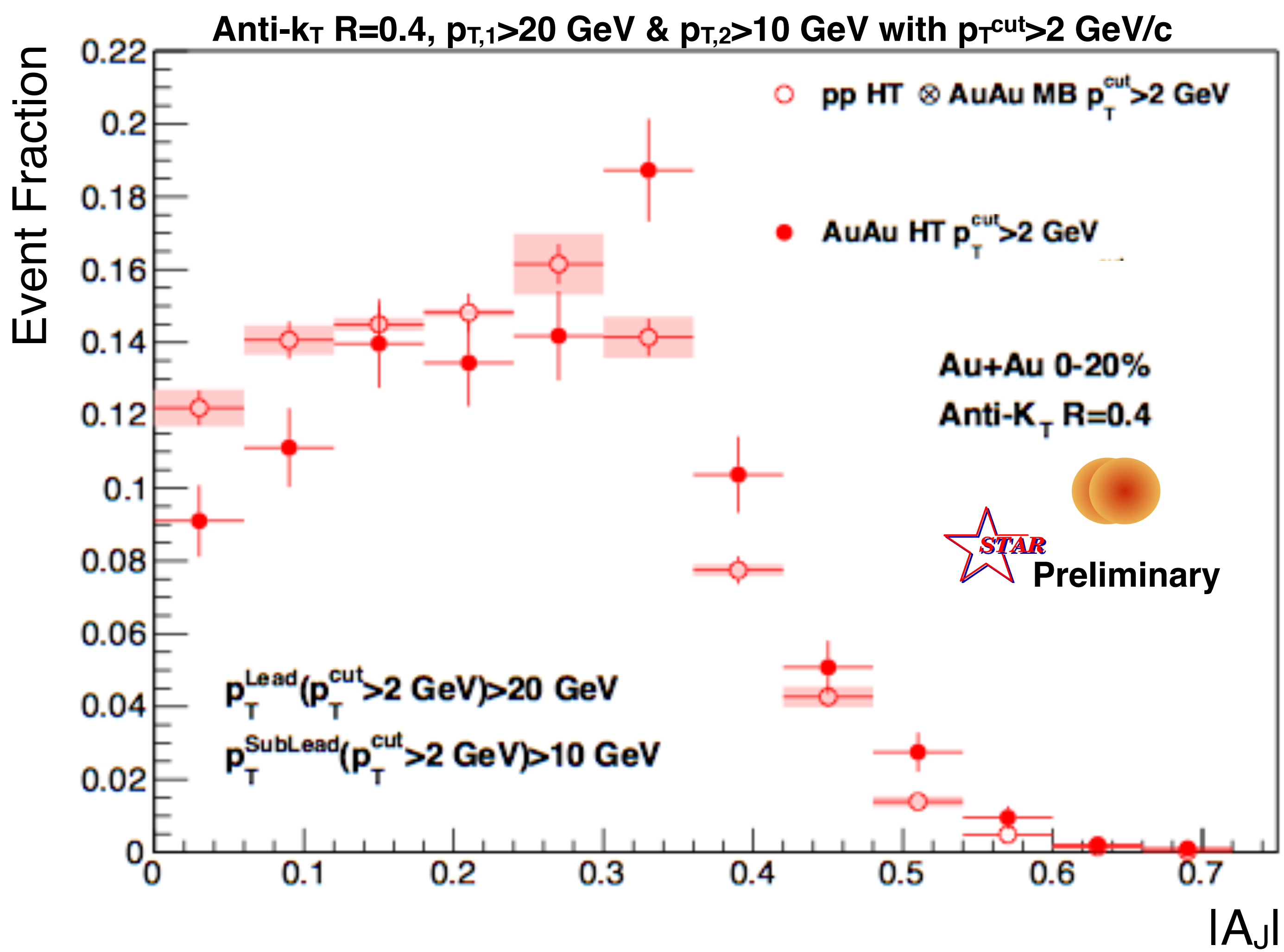
Calculate "matched" $|A_j|$ with constituent $p_{T,cut}$>0.2 GeV/c.

First (biased) Di-Jet Imbalance (A_J) Measurements at RHIC



Sys. Uncertainties:
- tracking eff. 6%
- tower energy scale 2%

First (biased) Di-Jet Imbalance (A_J) Measurements at RHIC



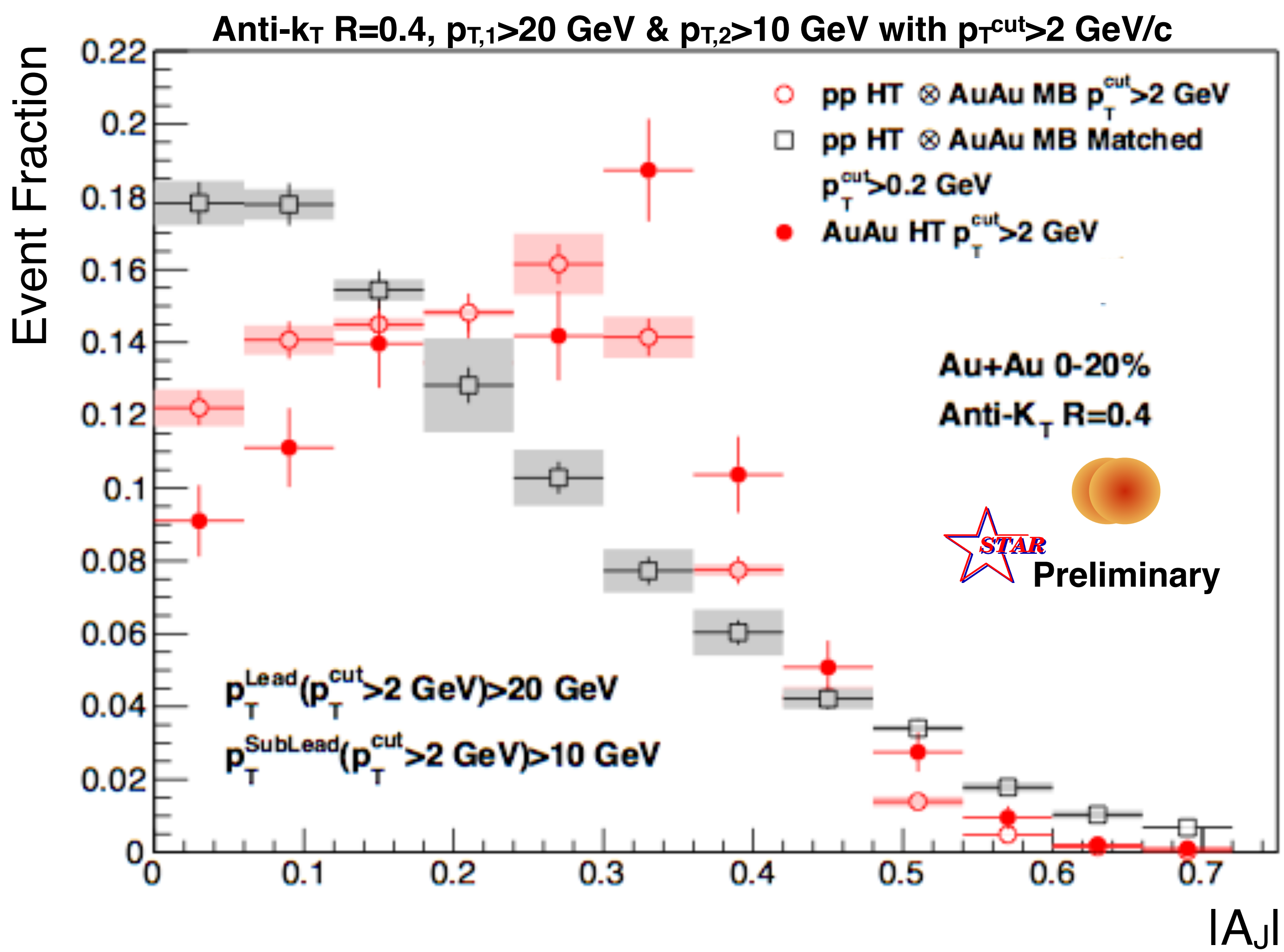
Sys. Uncertainties:
- tracking eff. 6%
- tower energy scale 2%

p-value<10^{-5}
(stat. error only)

Select modified di-jet pairs with p_T^{cut}>2 GeV/c in Au+Au

First (biased) Di-Jet Imbalance (A_J) Measurements at RHIC

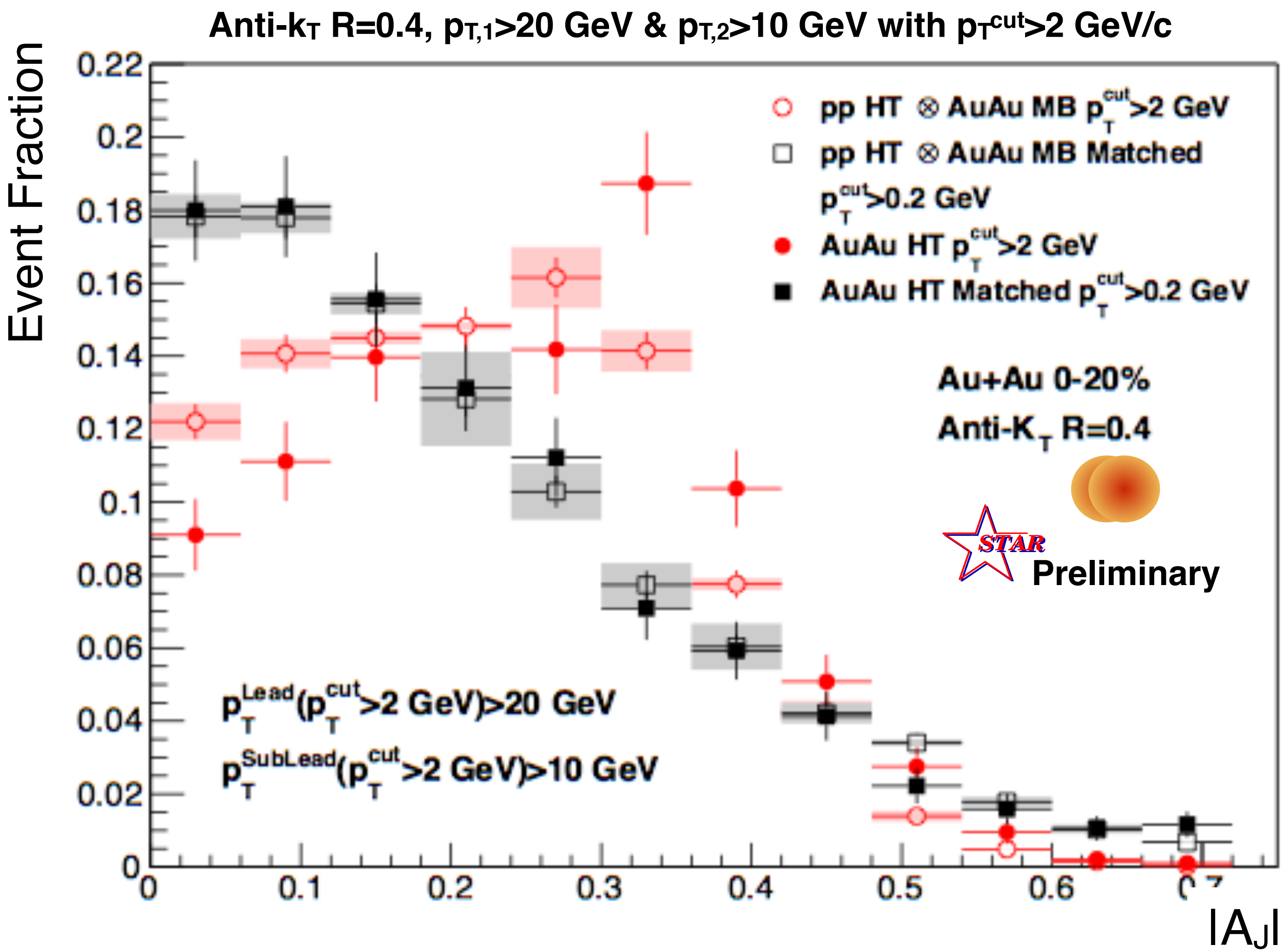
Sys. Uncertainties:
- tracking eff. 6%
- tower energy scale 2%



p-value$<10^{-5}$
(stat. error only)

Select modified di-jet pairs with $p_T^{cut}>2$ GeV/c in Au+Au

First (biased) Di-Jet Imbalance (A_J) Measurements at RHIC



Sys. Uncertainties:
- tracking eff. 6%
- tower energy scale 2%

p-value<10^{-5}
(stat. error only)

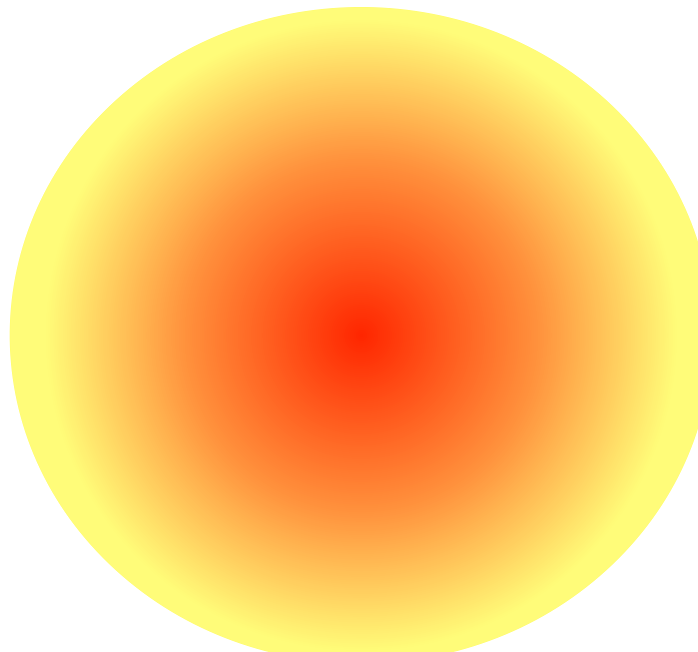
p-value~0.8
(stat. error only)

Select modified di-jet pairs with p_T^{cut}>2 GeV/c in Au+Au

→ Quenched jet energy is recovered at low p_T within a cone of R=0.4 (also jet broadening in 0.2 – 0.4 observed)

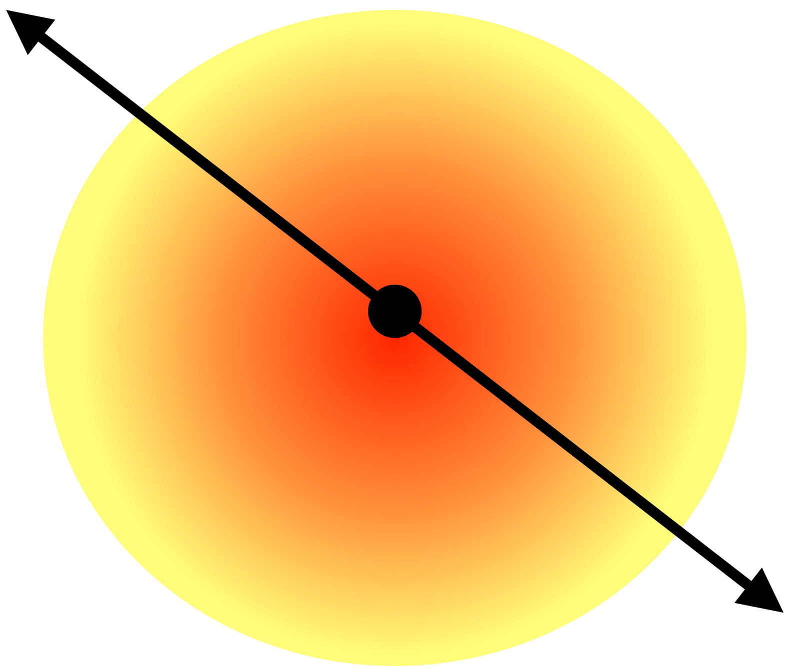
The Role of *Biases: Jet-Geometry-Engineering*

sPhenix*:* Made for it ;-)



The Role of *Biases: Jet-Geometry-Engineering*

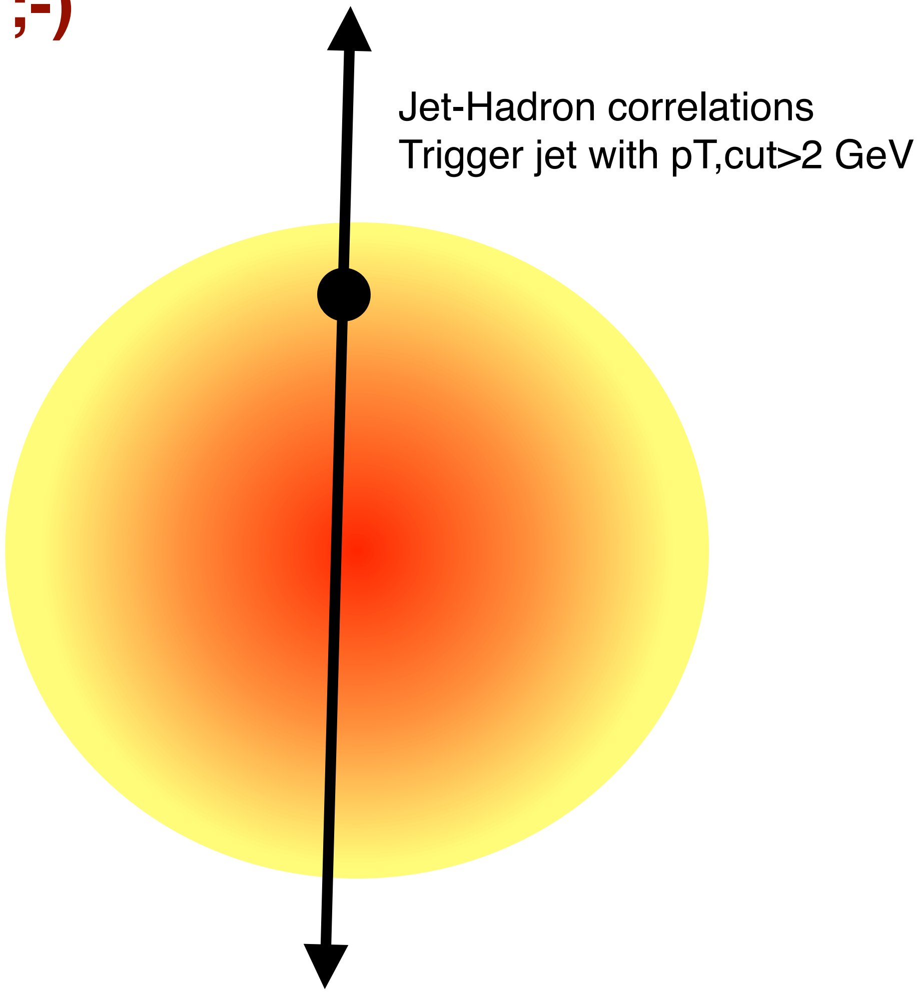
sPhenix*:* Made for it ;-)



Ideal Jet Finding
and direct-photon
correlations

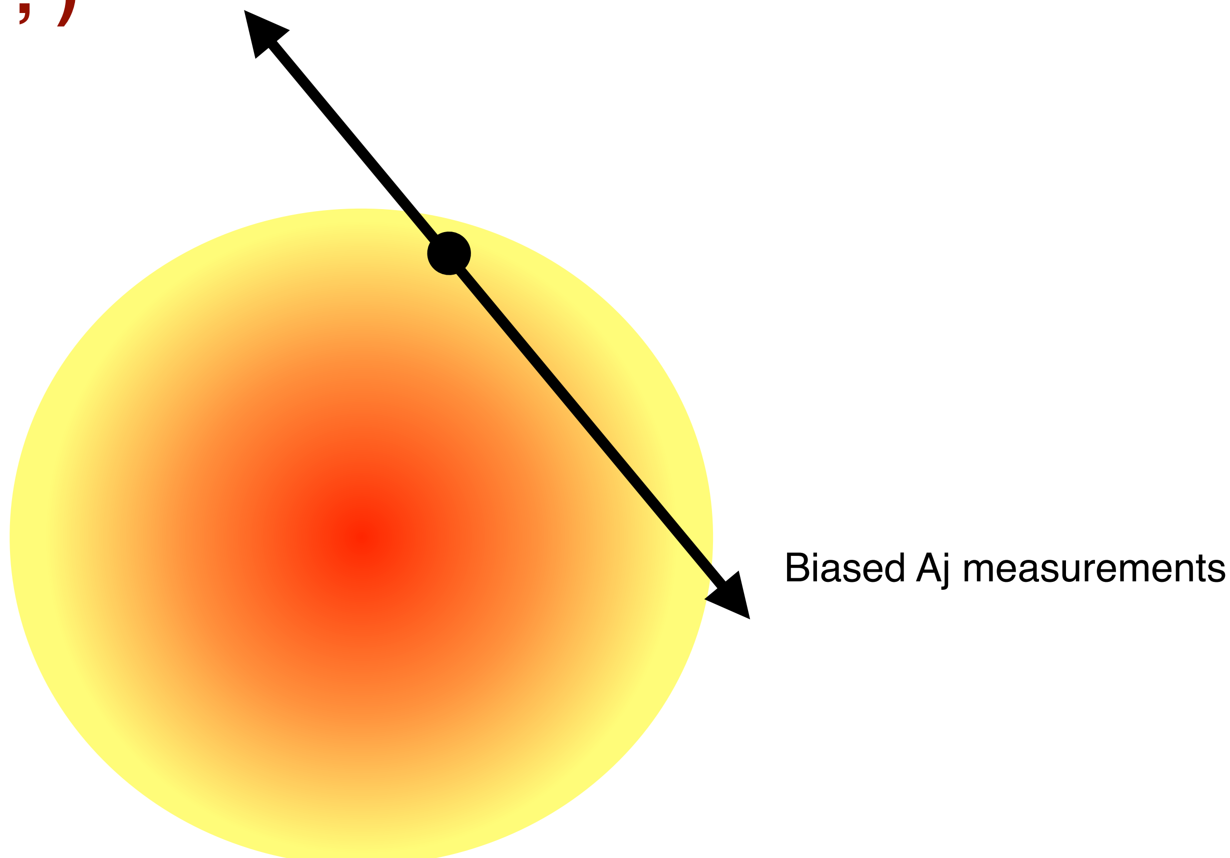
The Role of *Biases: Jet-Geometry-Engineering*

sPhenix*:* Made for it ;-)



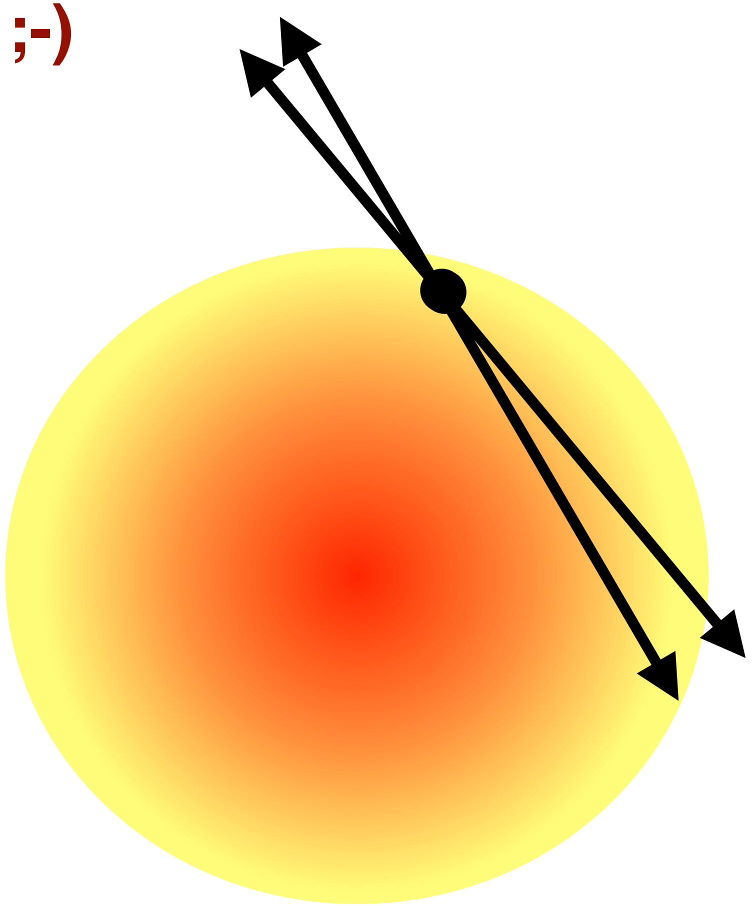
The Role of *Biases: Jet-Geometry-Engineering*

sPhenix*:* Made for it ;-)



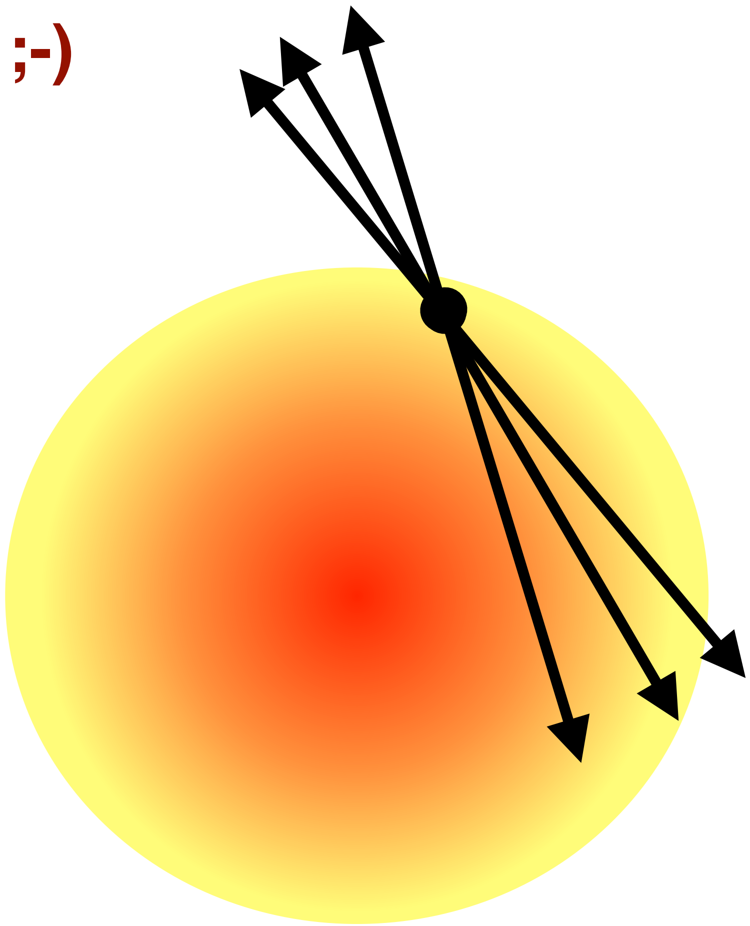
The Role of *Biases: Jet-Geometry-Engineering*

sPhenix*:* Made for it ;-)



The Role of *Biases: Jet-Geometry-Engineering*

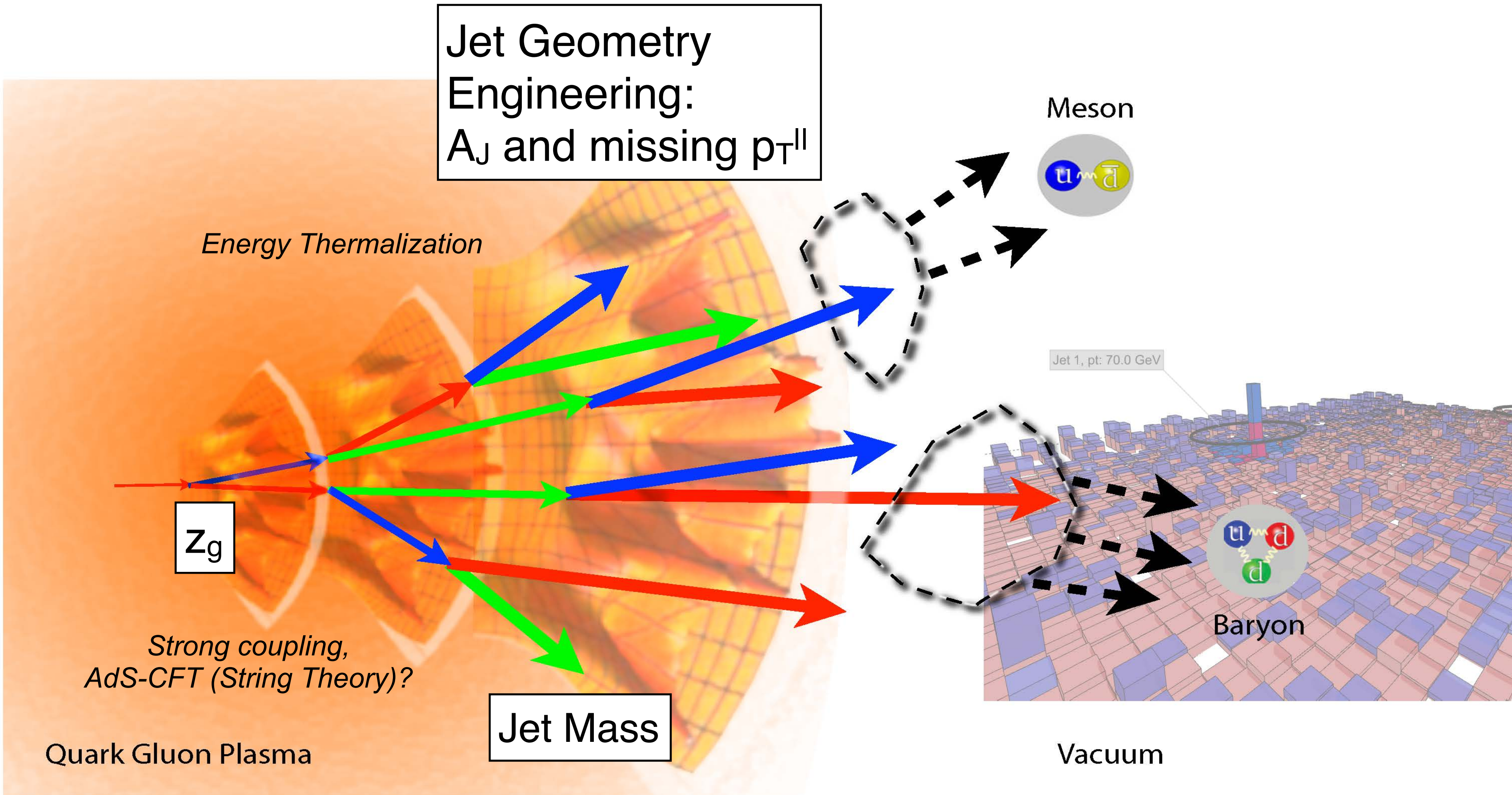
sPhenix*:* Made for it ;-)



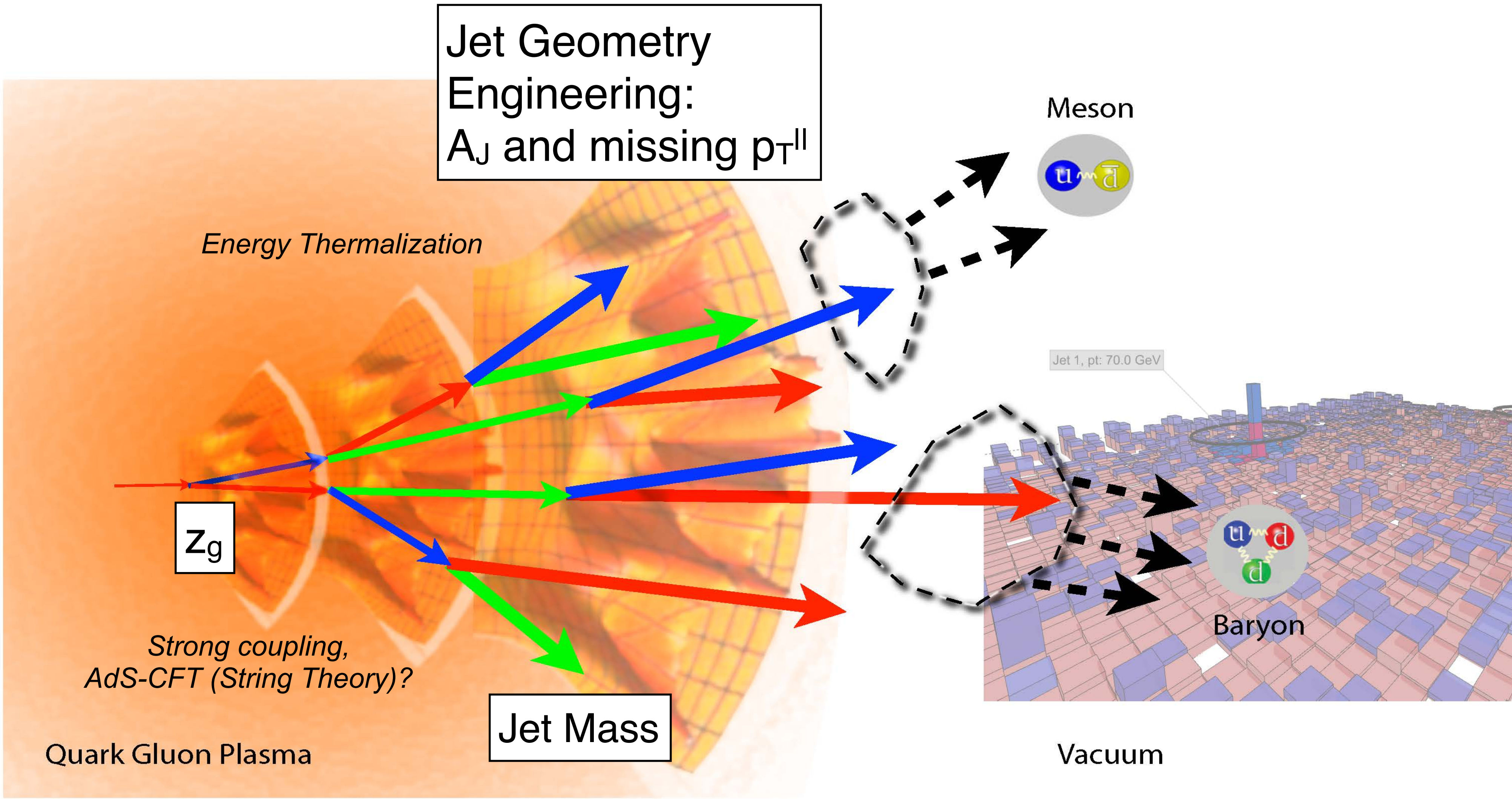
<u>Important Application:</u> We can select a biased di-jet sample in which the energy is recovered and we can turn it on/off = control!
Excellent tool to study soft gluon radiation and thermalization!

<u>Caveat:</u> Needs Jet Quenching MC Model for quantitative comparisons!

Jet Quenching in the QGP - Experimental Observables

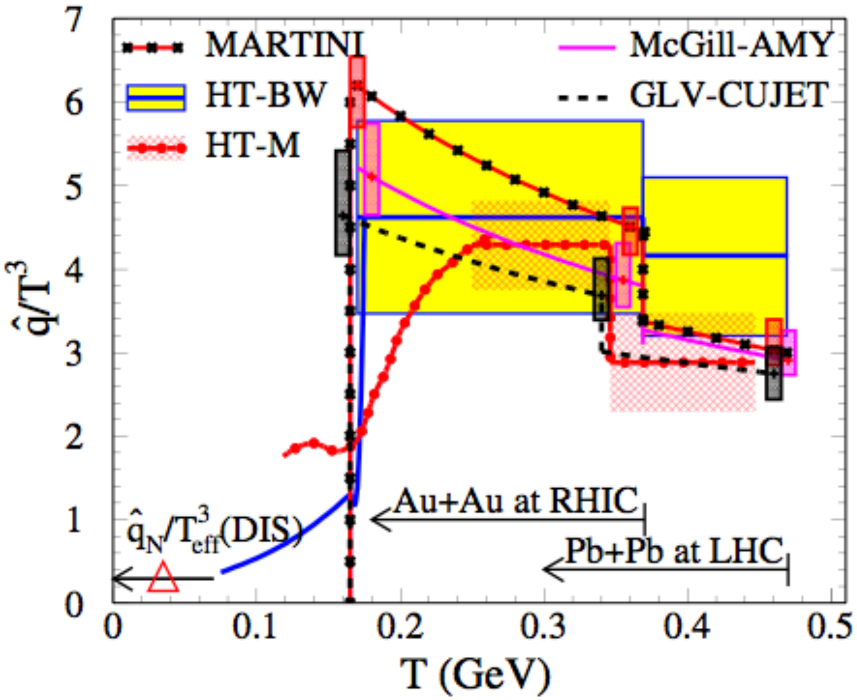


Jet Quenching in the QGP - Experimental Observables

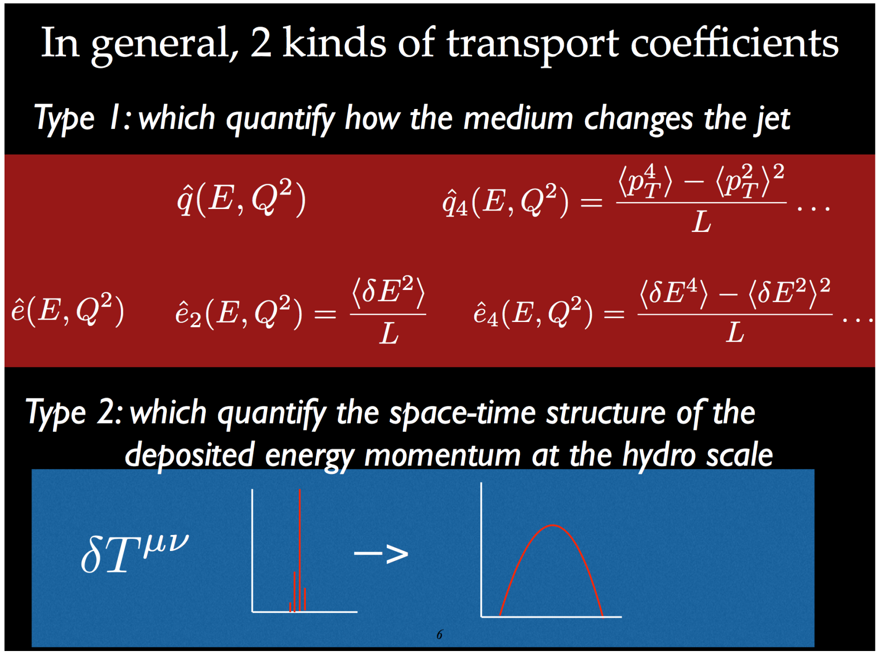


Can we follow the parton shower further?
z_g and Jet Mass of 2nd, 3rd, … split?

Crucial: Improvements in Theory



Talk by A. Majumder yesterday



(Full) Jet Measurements are necessary to determine Type 1 <u>and</u> Type 2 jet quenching transport coefficients

Next Gen Jet Quenching MC models needed!

We must (shall) work together to ensure success!

TechQM-like working group desirable!

A "RHIC Jet Working Group"?

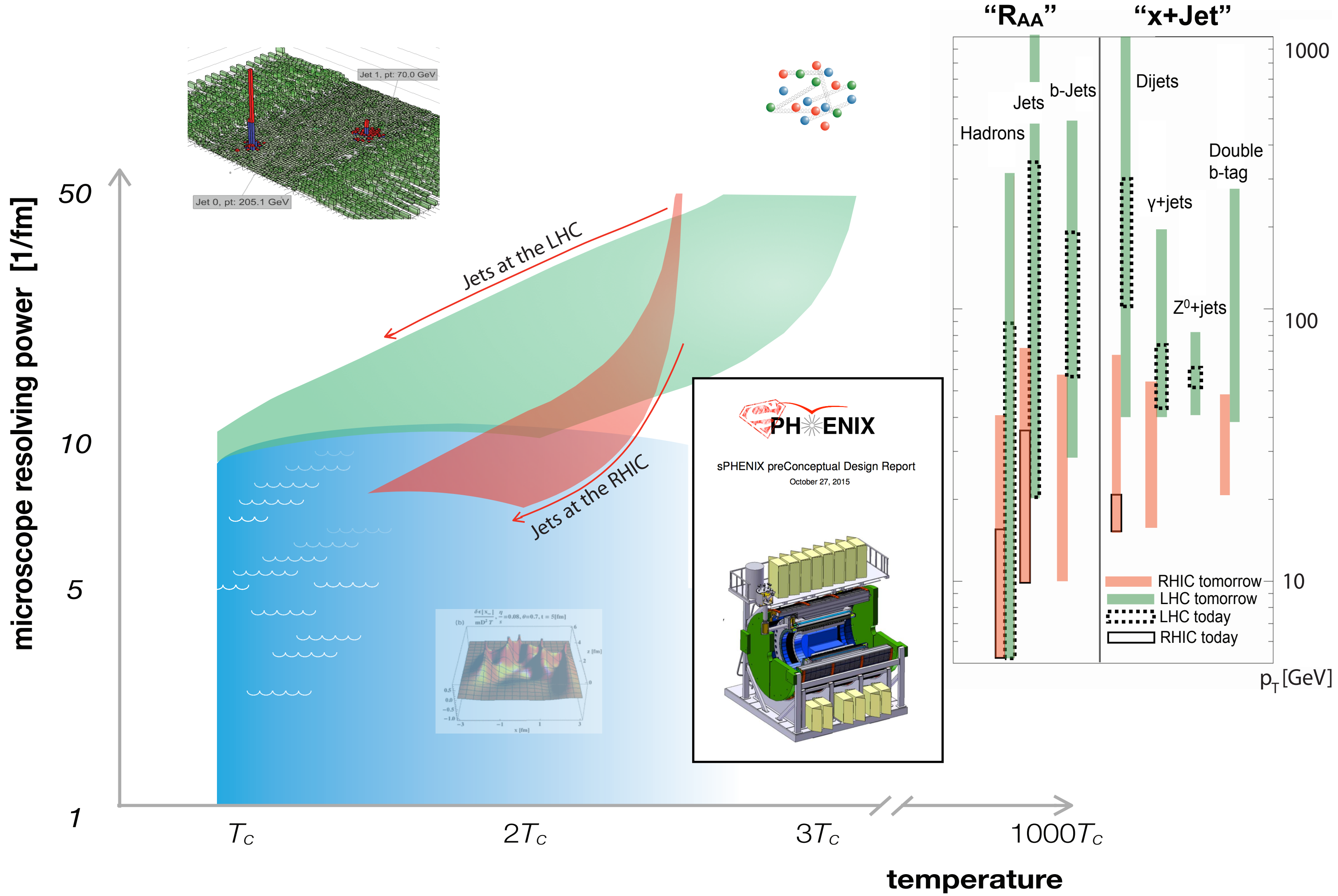
The time is now to work together (STAR & sPhenix) as a RHIC jet community!

Is it possible to establish a RHIC Jet Working Group (or whatever other appropriate name) in particular allowing access to STAR data to pursue/test/explore/learn RHIC jet measurements for interested sPhenix collaborators?

(Of course one has to carefully evaluate potential manpower issues …)

Summary

Hot QCD Matter White Paper, arXiv:1502.02730



Jet Measurements in sPhenix →
Answering Fundamental Questions of QCD (Matter)

Backup

Soft-Drop Algorithm

The soft drop declustering procedure depends on two parameters, a soft threshold z_{cut} and an angular exponent β, and is implemented as follows:

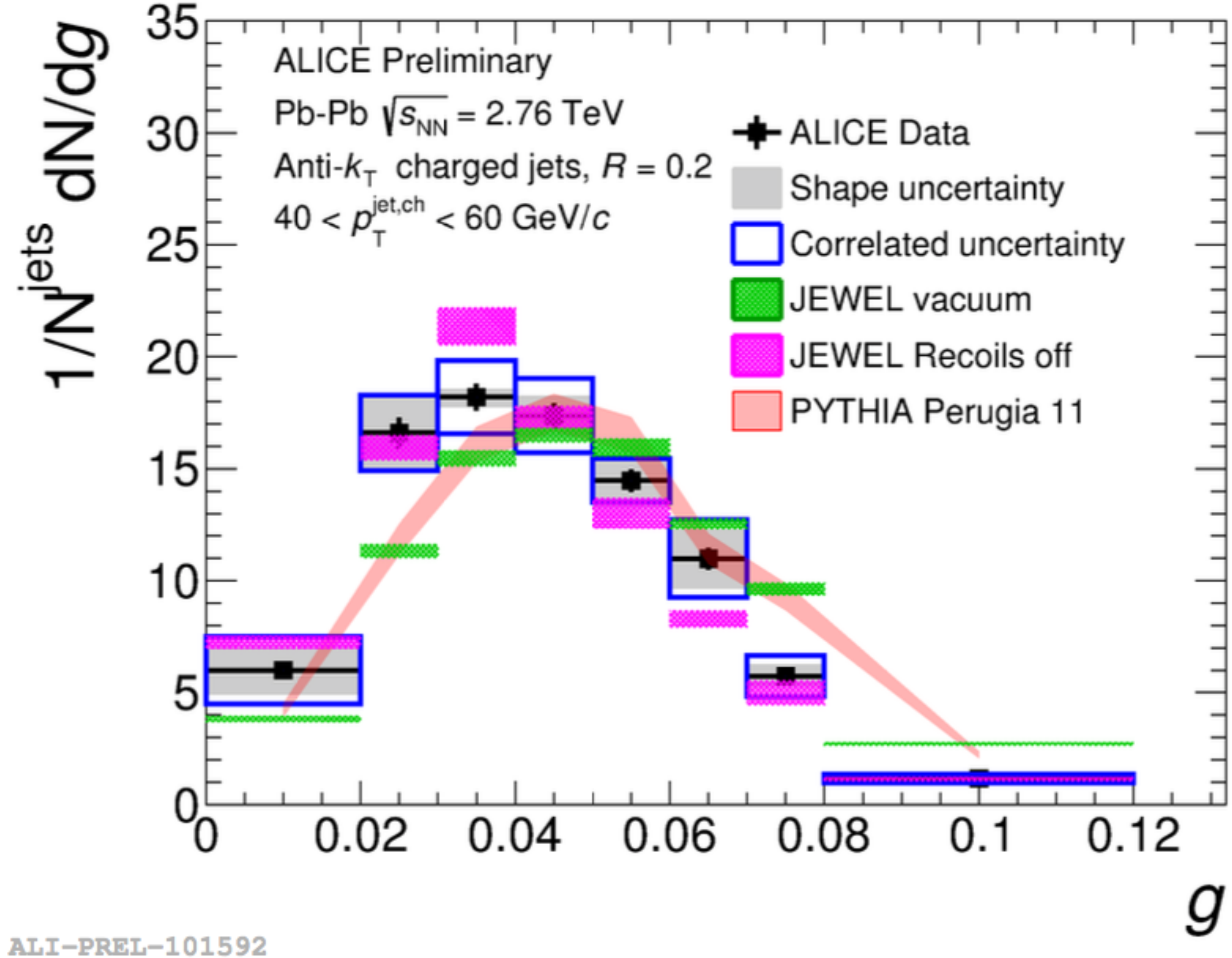
1. Break the jet j into two subjets by undoing the last stage of C/A clustering. Label the resulting two subjets as j_1 and j_2.

2. If the subjets pass the soft drop condition $\left(\frac{\min(p_{T1},p_{T2})}{p_{T1}+p_{T2}} > z_{\mathrm{cut}}\left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}\right.$, see Eq. (1.1)$\Big)$ then deem j to be the final soft-drop jet. (Optionally, one could also impose the mass-drop condition $\max(m_1, m_2) < \mu\, m$ as in Ref. [6], but we will not use that here.)

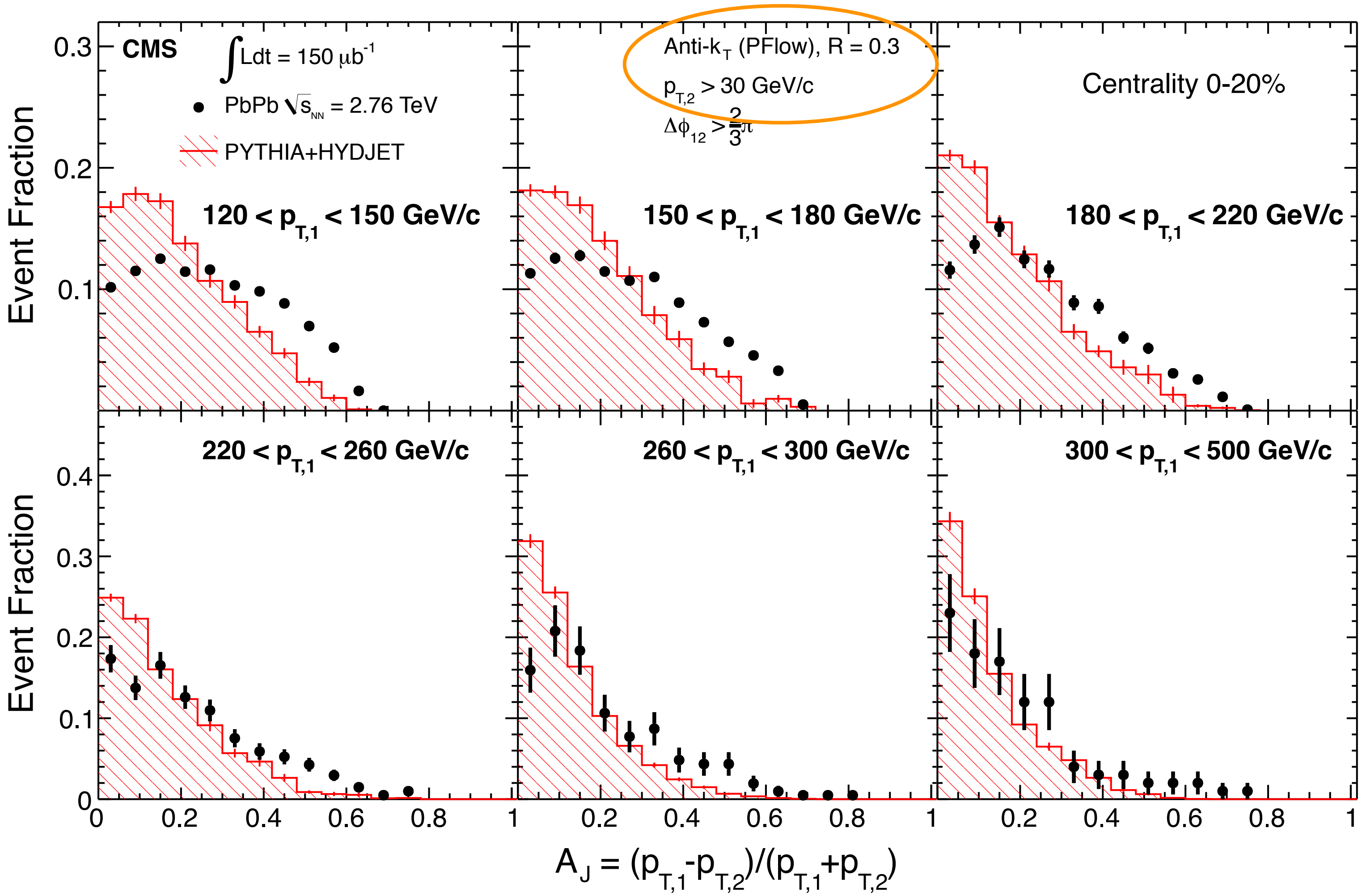
3. Otherwise, redefine j to be equal to subjet with larger p_T and iterate the procedure.

4. If j is a singleton and can no longer be declustered, then one can either remove j from consideration ("tagging mode") or leave j as the final soft-drop jet ("grooming mode").

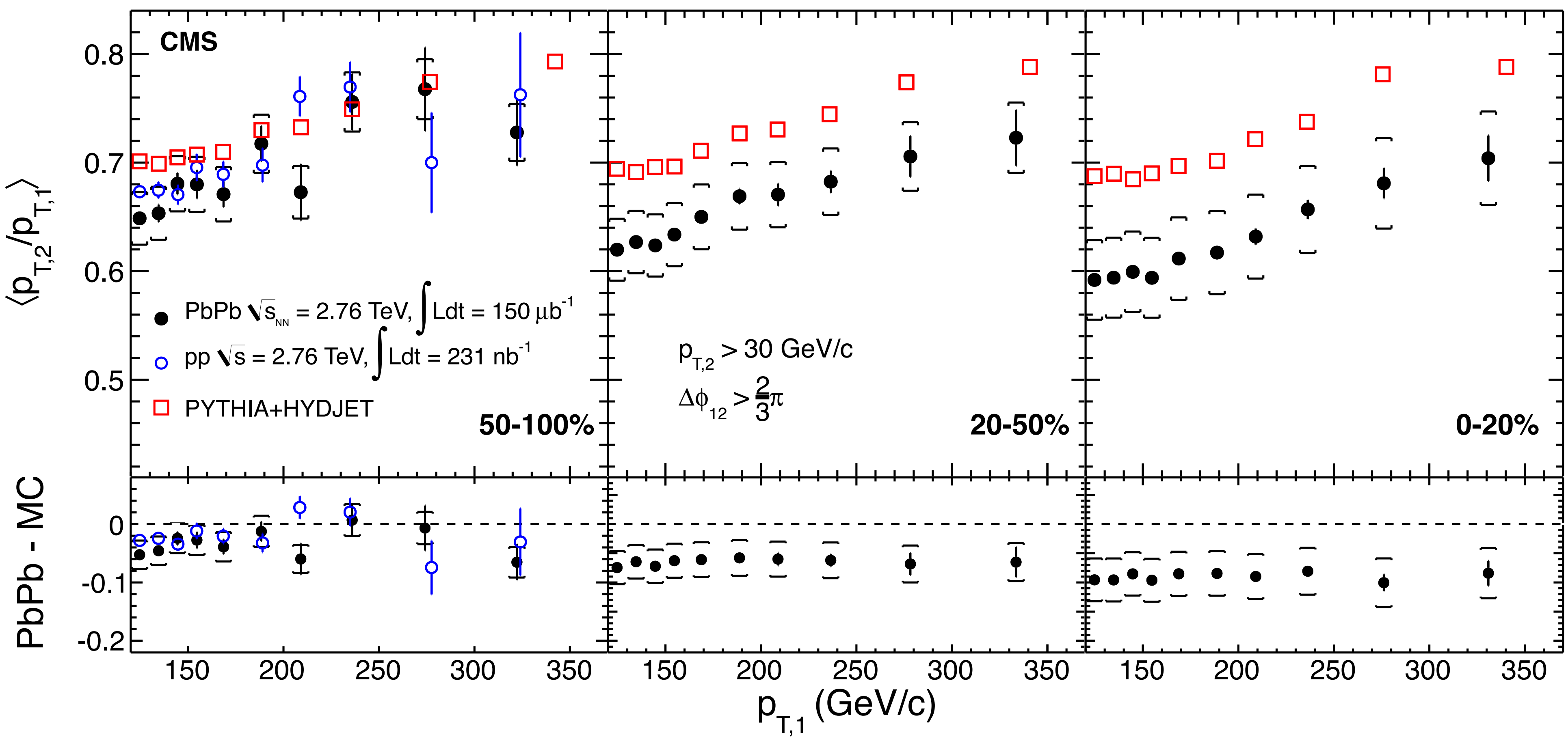
Jet Structure: Radial Moment



Di-jet Asymmetry/Imbalance as function of leading jet p_T



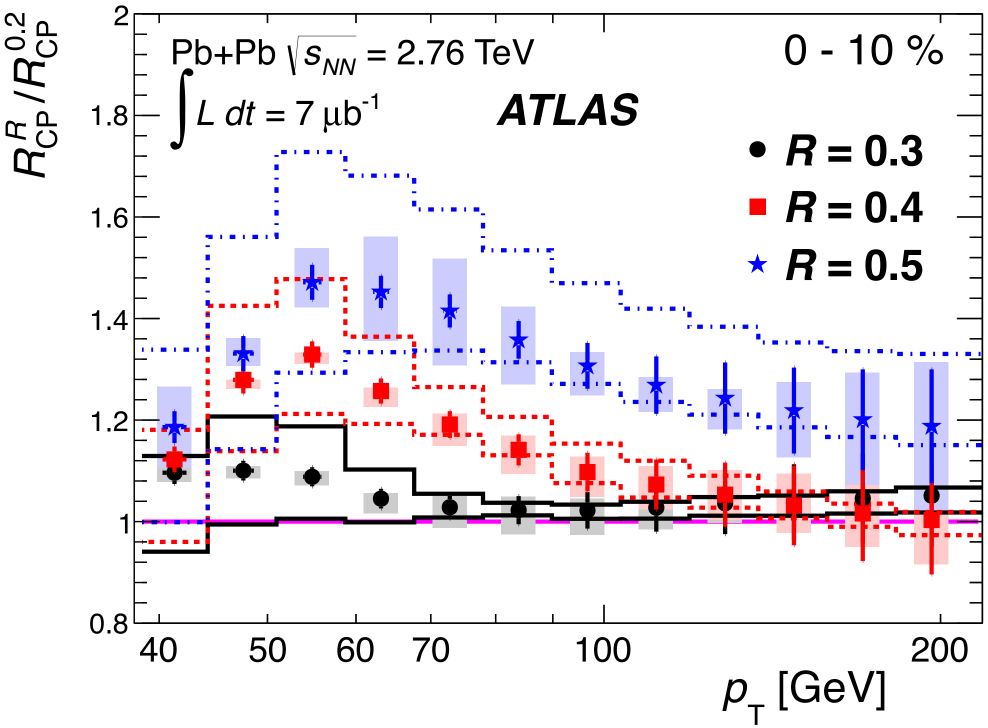
Di-jet Asymmetry/Imbalance as function of leading jet p_T

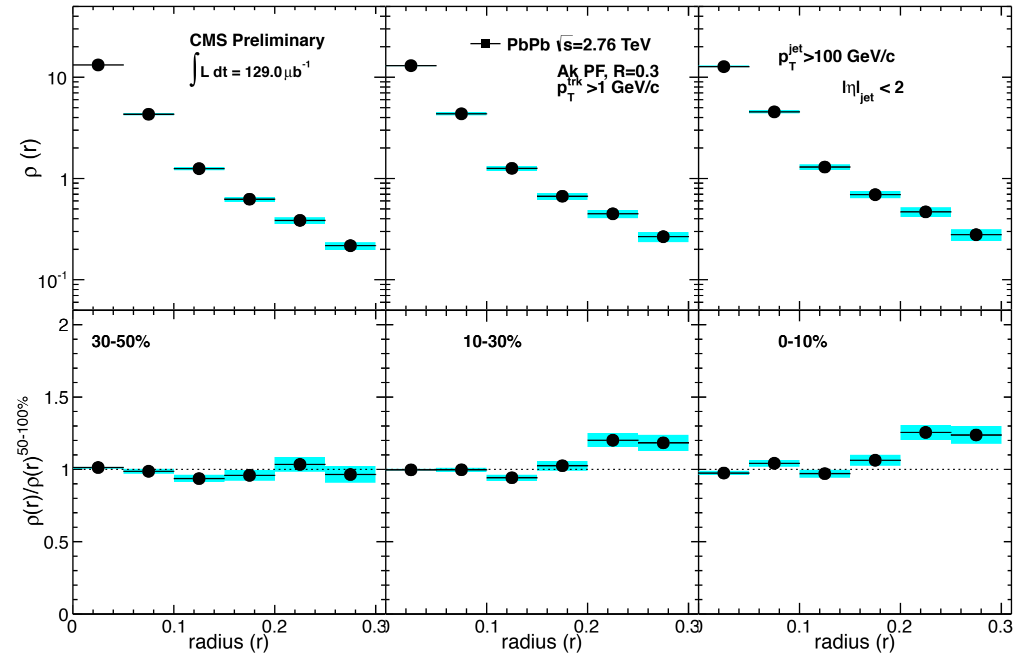


Di-Jet imbalance decreasing with increasing jet energy!

"Can be explained in terms of essentially known physics, i.e. the increased collimation of jets due to kinematics and a transition to a less gluon- dominated regime." : T.Renk, arXiv:1204.5572

Jet Structure in Pb-Pb Collisions cont.

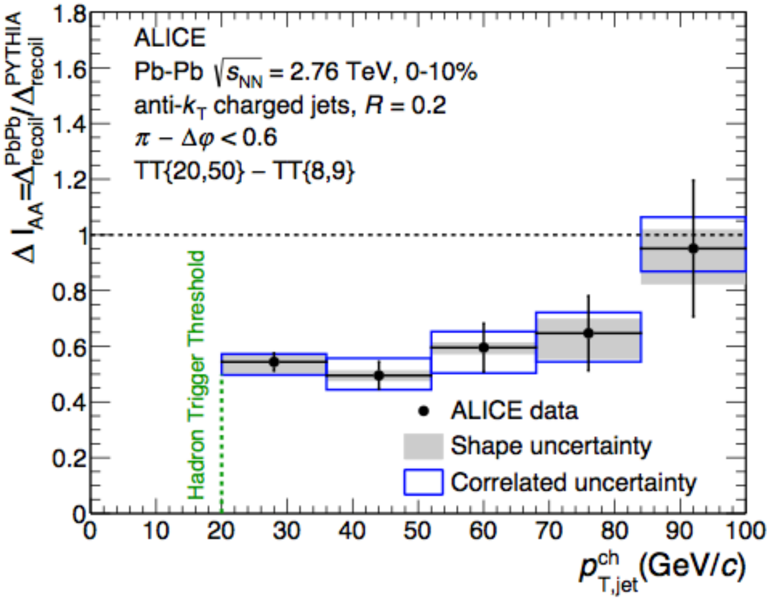


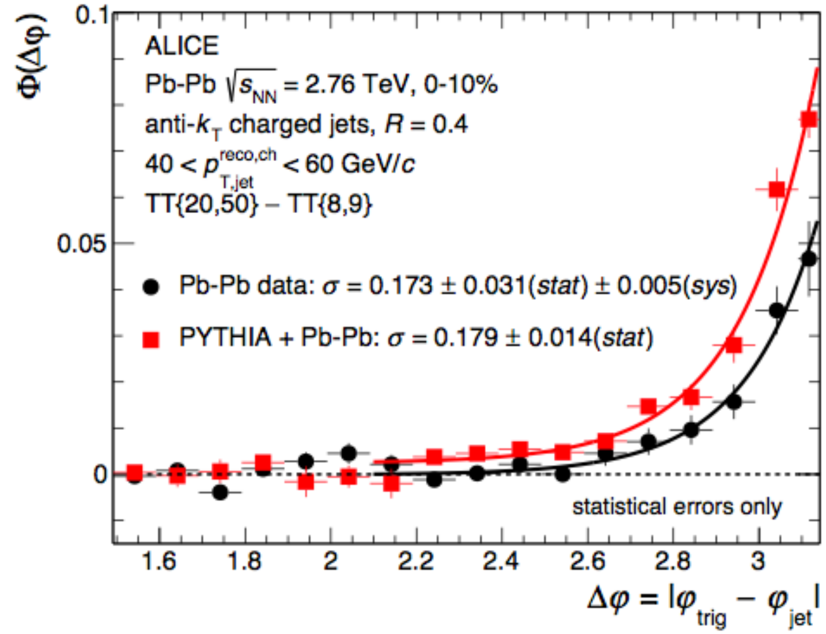


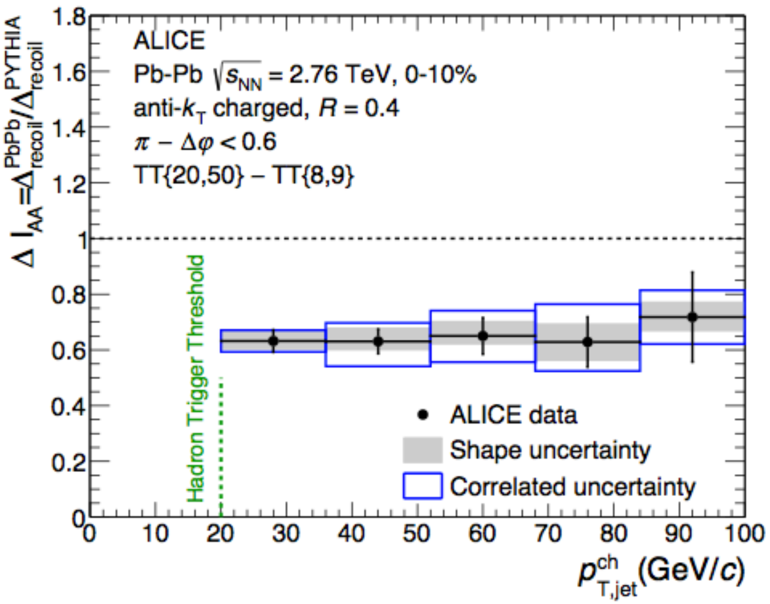
Modest jet broadening seen in differential jet shape and R dependence of jet R_{CP}

(especially at lower jet p_T)

Coincidence Measurements: h-Jet







Recoil spectrum suppressed

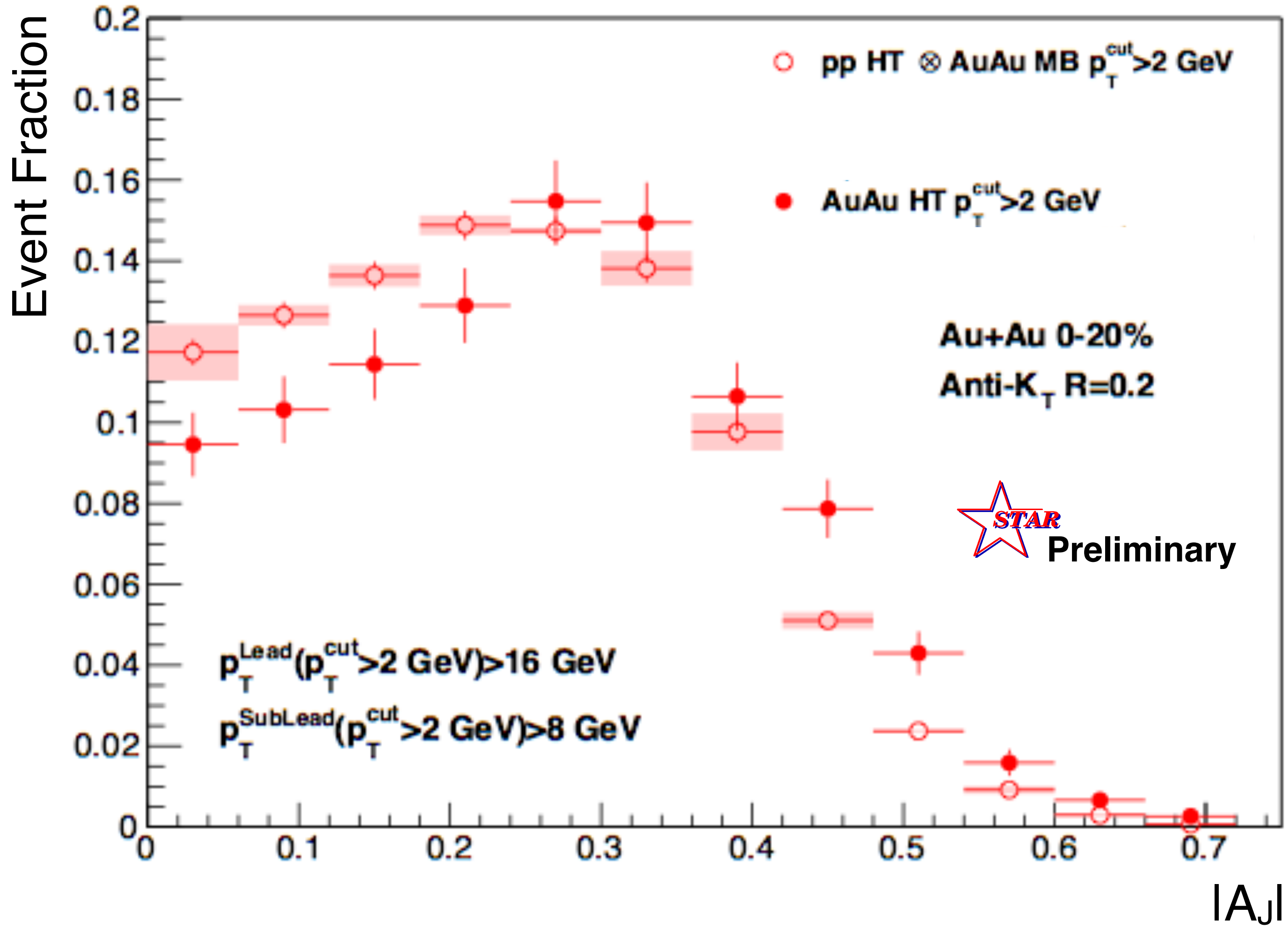
No significant broadening

No angular de-correlation

(also seen in h-jet @RHIC)

Di-Jet Imbalance A_J Au+Au 0-20% R=0.2

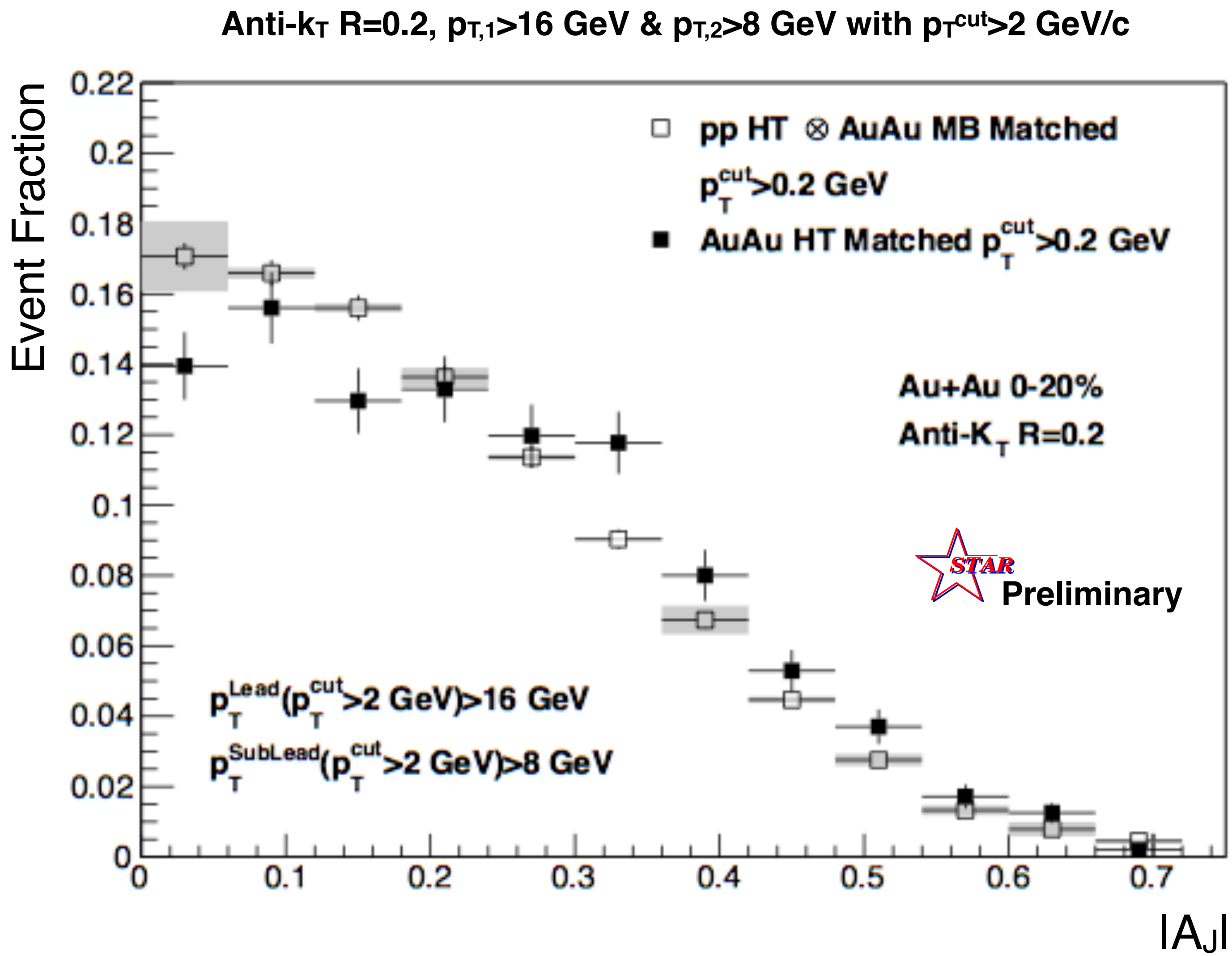
Anti-k_T R=0.2, $p_{T,1}$>16 GeV & $p_{T,2}$>8 GeV with p_T^{cut}>2 GeV/c



Sys. Uncertainties:
- tracking eff. 6%
- tower energy scale 2%

p-value<10^{-10}
(stat. error only)

Di-Jet Imbalance A_J Au+Au 0-20% R=0.2



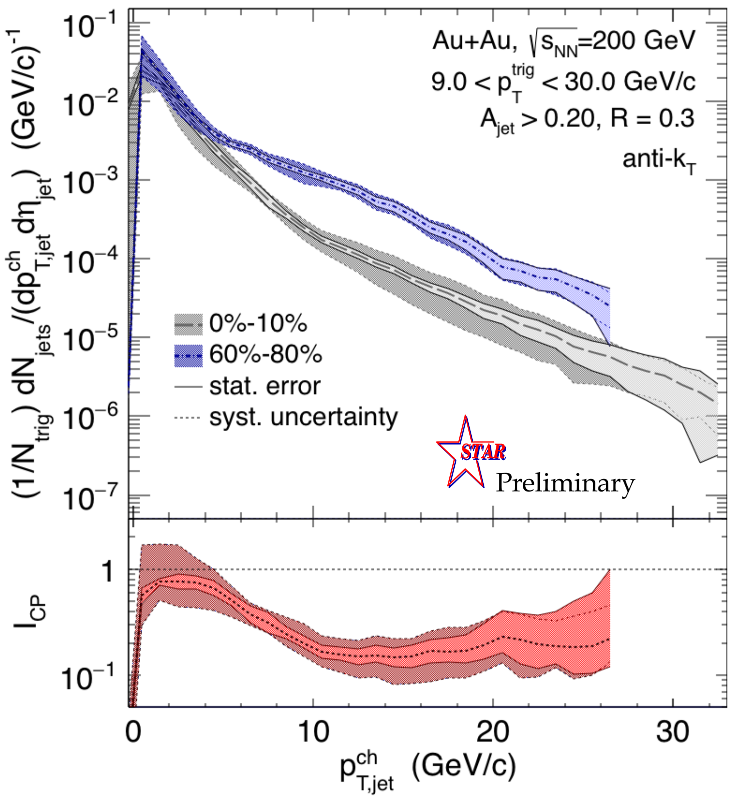
Sys. Uncertainties:
- tracking eff. 6%
- tower energy scale 2%

p-value<10^{-10} (stat. error only)

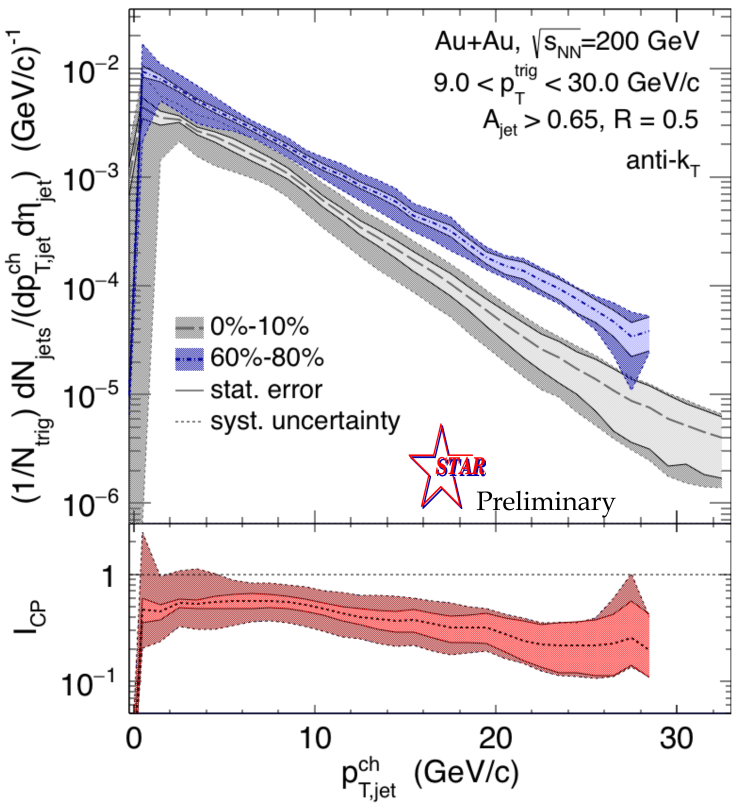
p-value<10^{-4} (stat. error only)

Matched Au+Au A_J ≠ p+p A_J for R=0.2
→ (recoil) Jet broadening in 0.2 – 0.4

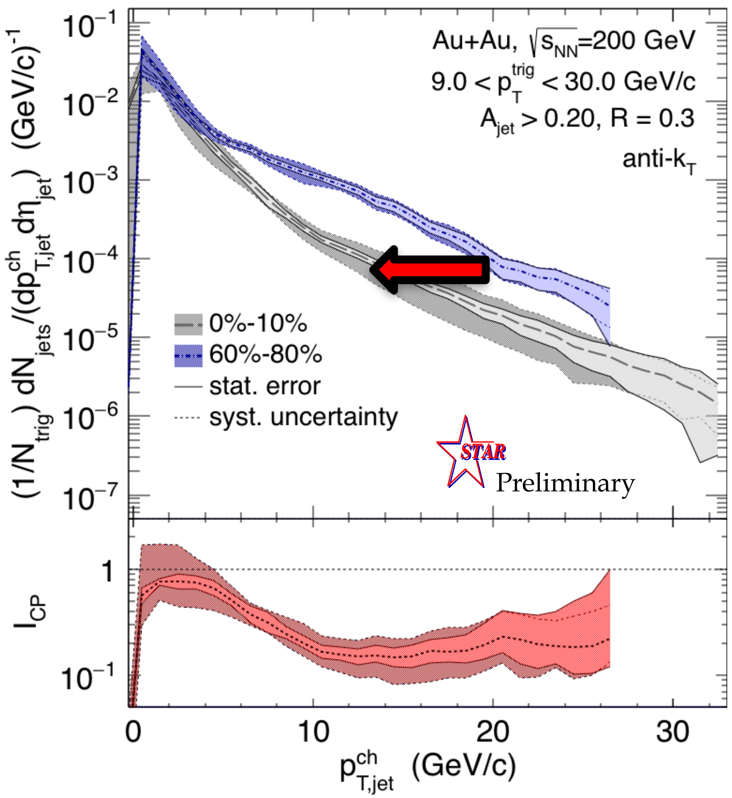
R=0.3


Au+Au, $\sqrt{s_{NN}}$=200 GeV
9.0 < p_T^{trig} < 30.0 GeV/c
A_{jet} > 0.20, R = 0.3
anti-k_T
0%-10%
60%-80%
stat. error
syst. uncertainty
STAR
Preliminary
$(1/N_{trig})\ dN_{jets}/(dp^{ch}_{T,jet}d\eta_{jet})$ $(GeV/c)^{-1}$
I_{CP}
$p^{ch}_{T,jet}$ (GeV/c)

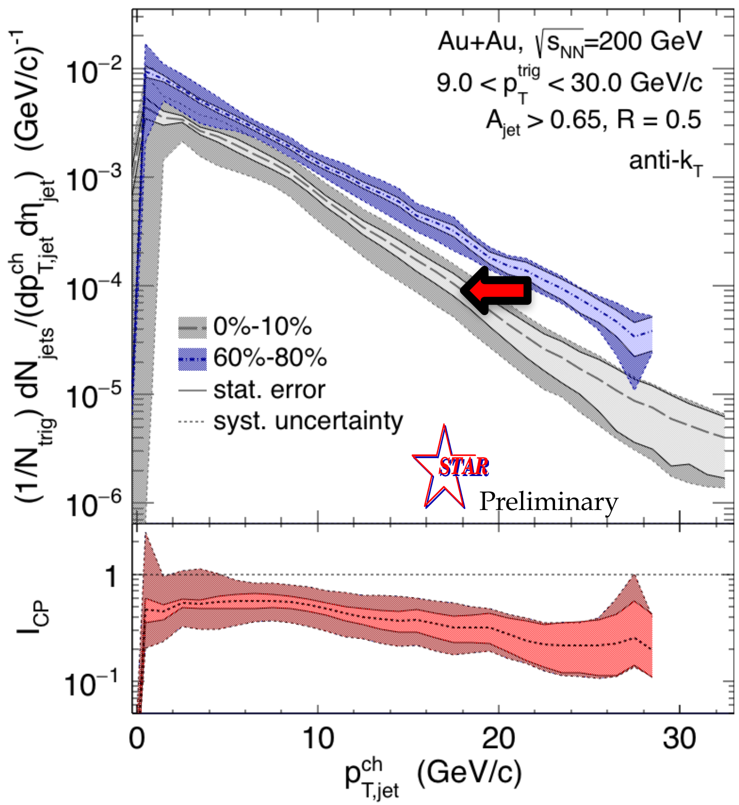
R=0.5


Au+Au, $\sqrt{s_{NN}}$=200 GeV
9.0 < p_T^{trig} < 30.0 GeV/c
A_{jet} > 0.65, R = 0.5
anti-k_T
0%-10%
60%-80%
stat. error
syst. uncertainty
STAR
Preliminary
$(1/N_{trig})\ dN_{jets}/(dp^{ch}_{T,jet}d\eta_{jet})$ $(GeV/c)^{-1}$
I_{CP}
$p^{ch}_{T,jet}$ (GeV/c)

R=0.3



R=0.5



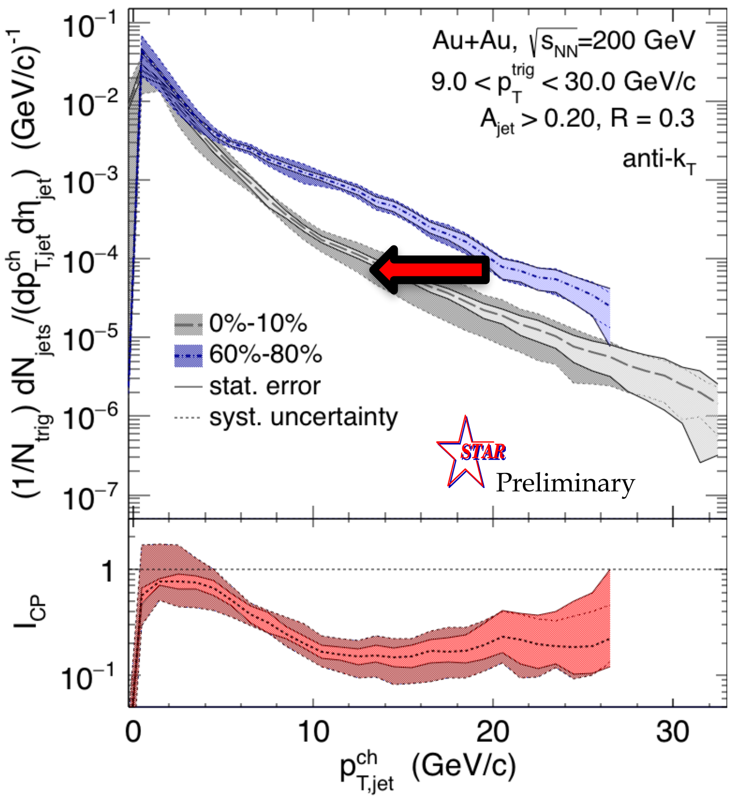
Calculate spectrum shift

- requires distributions ~ exponential, ratio ~ flat

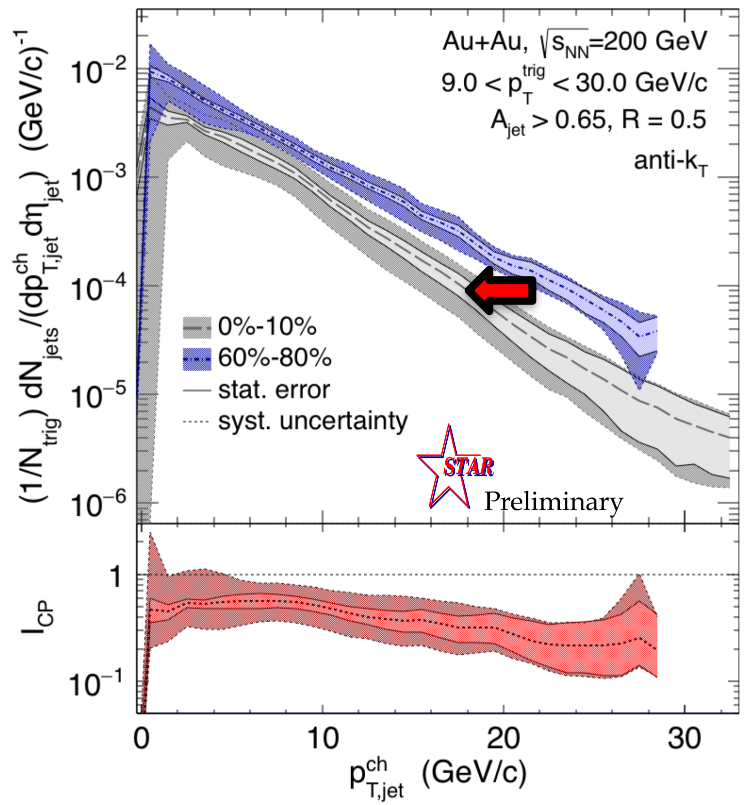
Spectrum Shift Periph/pp →Central

	$p^{ch}_{T,jet}$ range [GeV]	**Shift R=0.3 [GeV]**	**Shift R=0.5 [GeV]**
Au+Au @ 200 GeV	[10,20]	**-6.3** ± 0.6 ± 0.8	**-3.8** ± 0.5 ± 1.8
Pb+Pb @ 2.76 TeV *ALICE arXiv:1506.03984*	[60,100]		**-8** ± 2

R=0.3



R=0.5



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Au+Au @ 200 GeV	[10,20]	**-6.3** ± 0.6 ± 0.8	**-3.8** ± 0.5 ± 1.8
Pb+Pb @ 2.76 TeV *ALICE arXiv:1506.03984*	[60,100]		**-8** ± 2

RHIC: smaller shift for larger R

R=0.5: smaller shift at RHIC than LHC

Out-of-cone energy transport ?

- comparison requires similar trigger bias → theory calculation